Source: CERN

Numerical tools to quantify field quality in high-field magnets

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T-A formulation

- Proposed in Zhang et al. 2017 *Supercond Sci. Technol.* **30** 024005
- Particularly efficient to simulate coated conductors in 2D
- Superconducting layer assumed infinitely thin
  - Width: 4-12 mm
  - Thickness: a few micrometers
  - Very large width-to-thickness ratio

T-*A* formulation

- Magnetic vector potential ***A*** to calculate magnetic field everywhere
- Current vector potential ***T*** to calculate current in the superconductor
- In COMSOL Multiphysics
  - Magnetic field module (mf) for *A*-part
  - PDE (reduced dimensions) for *T*-part

$$\nabla \times (\nabla \times \mathbf{A}) = \mu \mathbf{J}$$

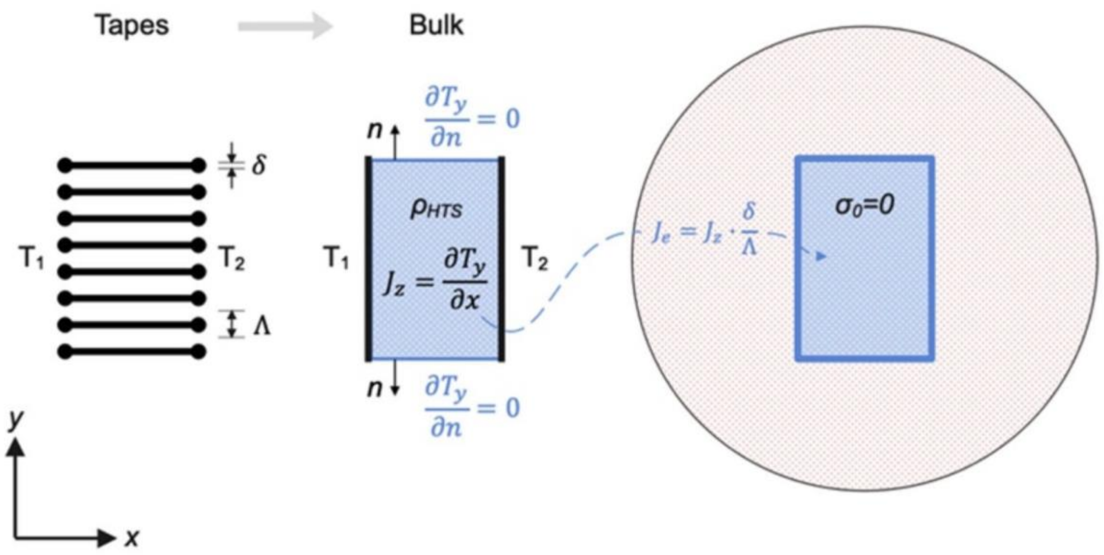
$$\nabla \times (\rho \nabla \times \mathbf{T}) = -\frac{\partial \mathbf{B}}{\partial t}$$

- Superconductor's resistivity

$$\rho(J) = \frac{E_\mathrm{c}}{J_\mathrm{c}(\mathbf{B})} \left| \frac{J}{J_\mathrm{c}(\mathbf{B})} \right|^{n(\mathbf{B})-1}$$

Homogenization

- ❑ Individual turns homogenized as a bulk conductor (reduction of DOFs)
- ❑ Same current per tape condition maintained
- ❑ Still only one component of ***T***



Source: Huber *et al.* 2022 *Superconductor Sci. Technol.* **35** 043003

Equations in cylindrical coordinates

$$\nabla \times (\nabla \times \mathbf{A}) = \mu \mathbf{J}$$

$$\nabla^2 A_\varphi = -\mu J_\varphi$$

$$\nabla \times (\rho \nabla \times \mathbf{T}) = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\frac{\partial}{\partial z}\left(\rho_{\mathrm{HTS}} \frac{\partial T_r}{\partial z}\right) = \frac{\partial B_r}{\partial t}$$

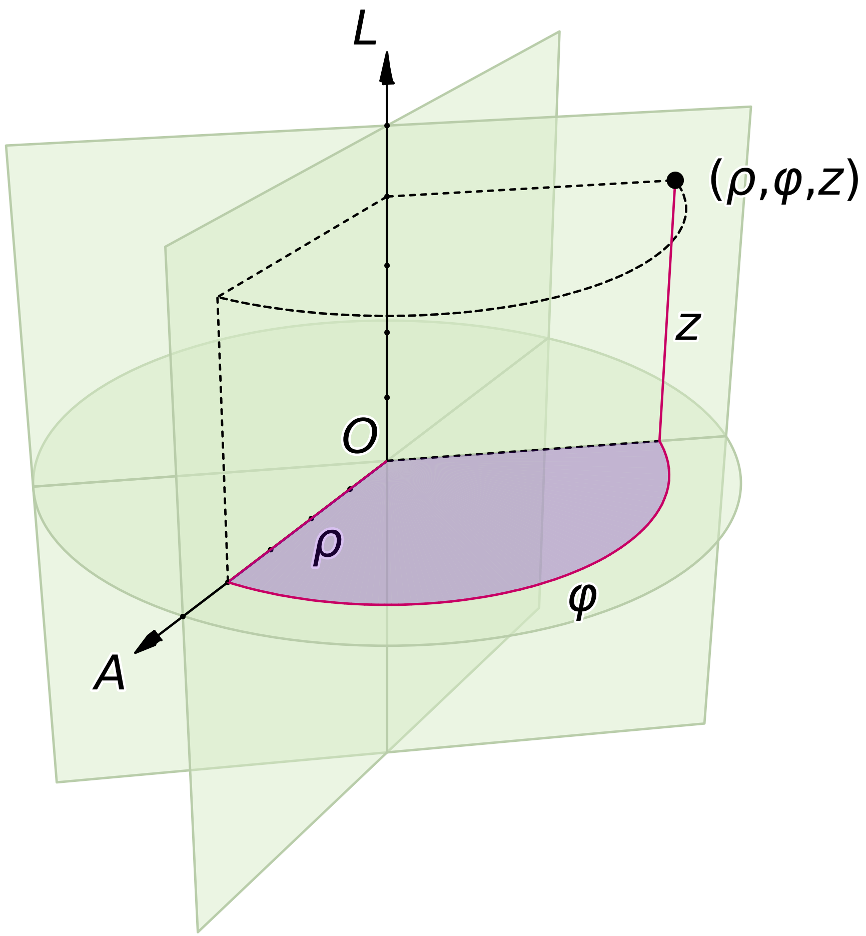


Figure by Jorge Stolfi - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=6692609

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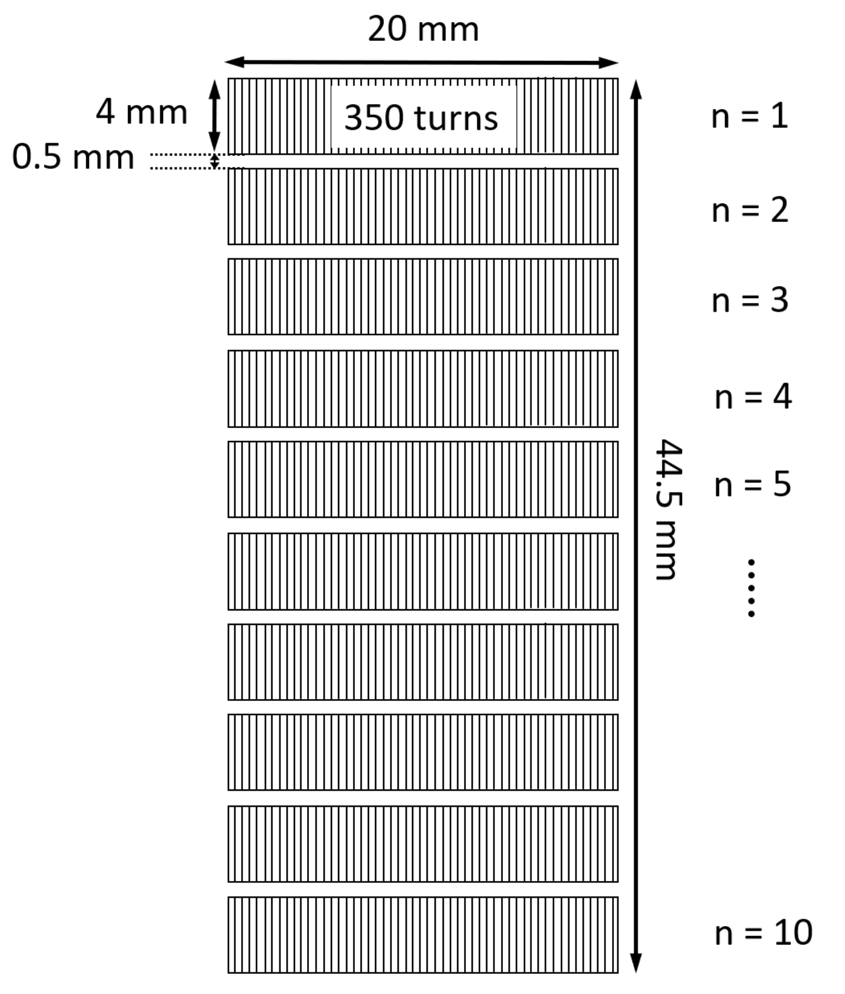
Simulations parameters

2G-HTS Parameters

Parameter	Value
Tape Width	0.004 m
Tape Thickness	5.7143×10^{-5} m
HTS Layer Thickness	1 μm
Jc0 (20K)	5.49×10^{11} A/m^2
Power-law Index (n)	25

Pancake Coil Geometry

Parameter	Value
Inner Radius	0.02 m
Outer Radius	0.04 m
Num. Tapes	350
Num. Pancakes	10



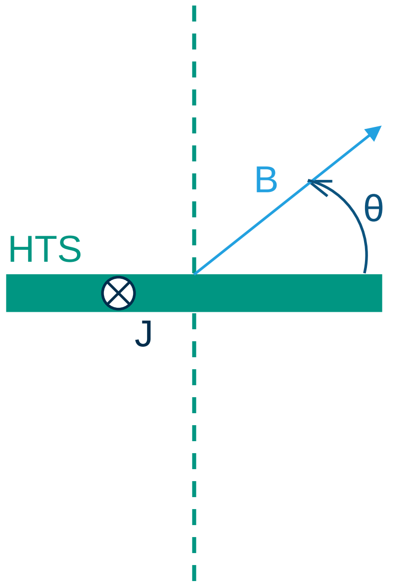
Dependence of critical current on magnetic field

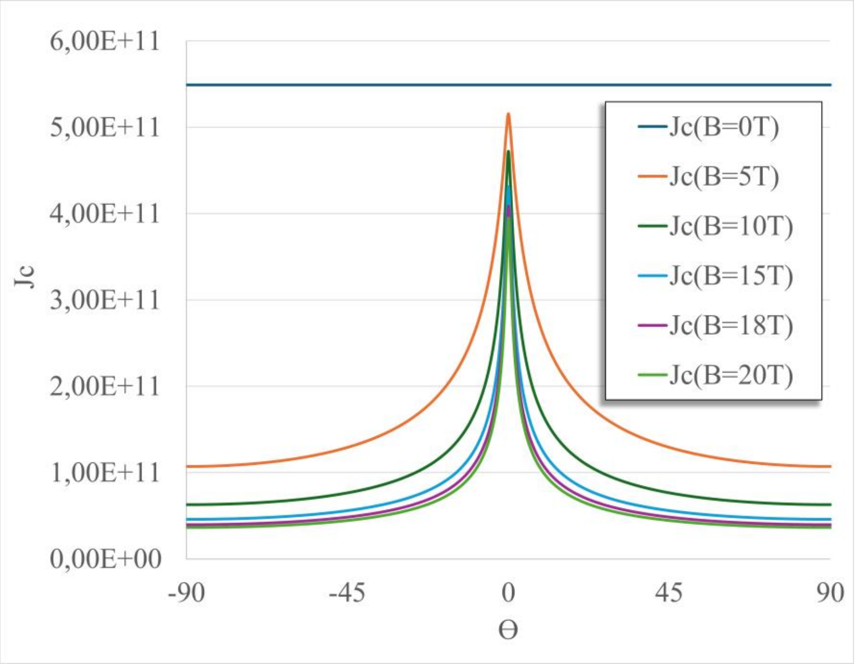
Modified Kim model

$$J_c(B,\theta) = J_{c0}\left(1 + \epsilon_\theta \left(\frac{B}{B_0}\right)^{\alpha}\right)^{-\beta}$$

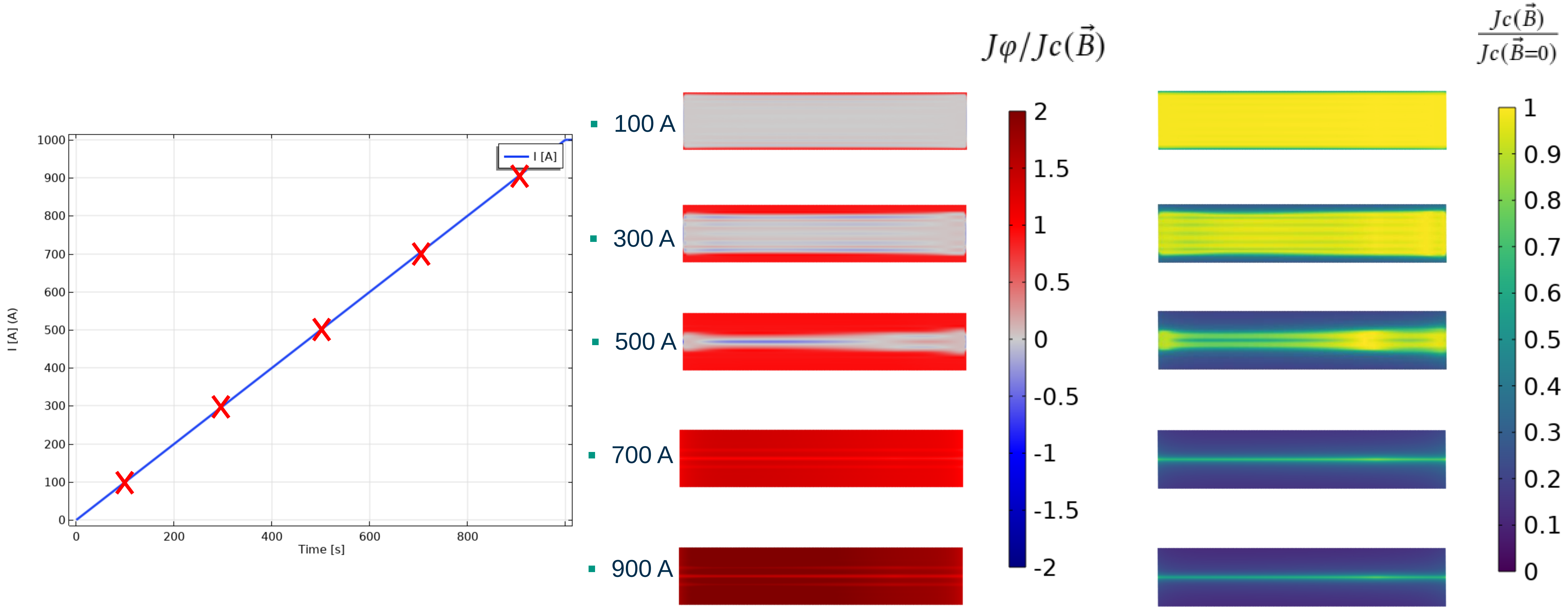
$$\varepsilon_\theta = \sqrt{\gamma^{-1}\cos^2(\theta) + \sin^2(\theta)}.$$

Parameter	Value
I_{c0} (T=20K)	2196 A
B0	0.6736 T
γ	18490
α	1.368
β	0.5829



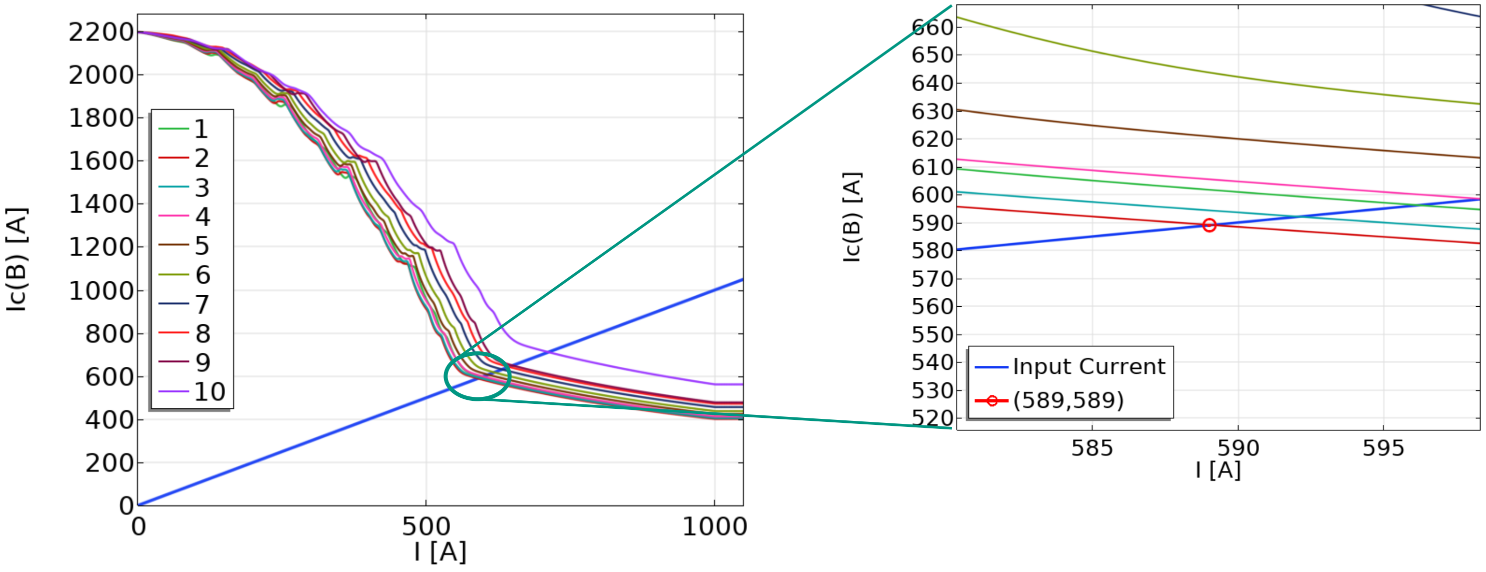


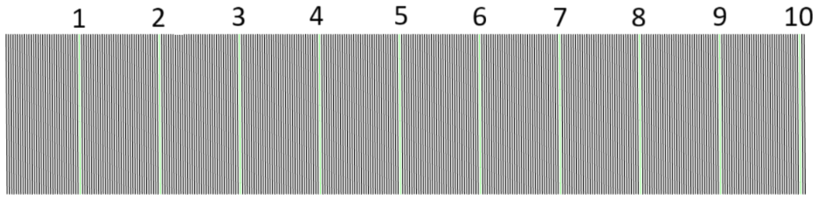
Current density distribution in a single pancake coil



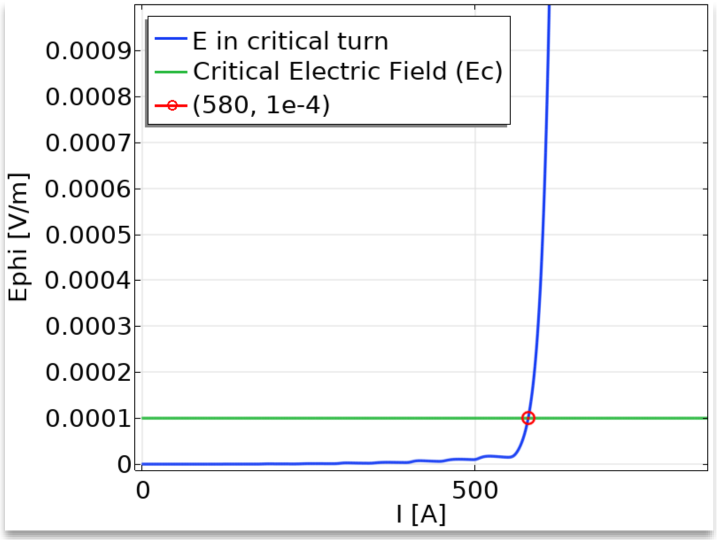
Maximum input current for a single pancake coil

Load line method



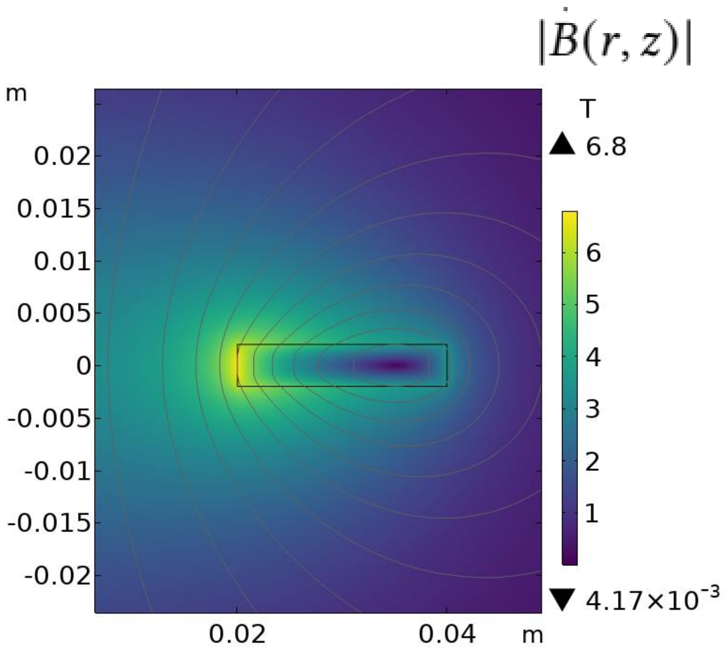


Voltage-current characteristic

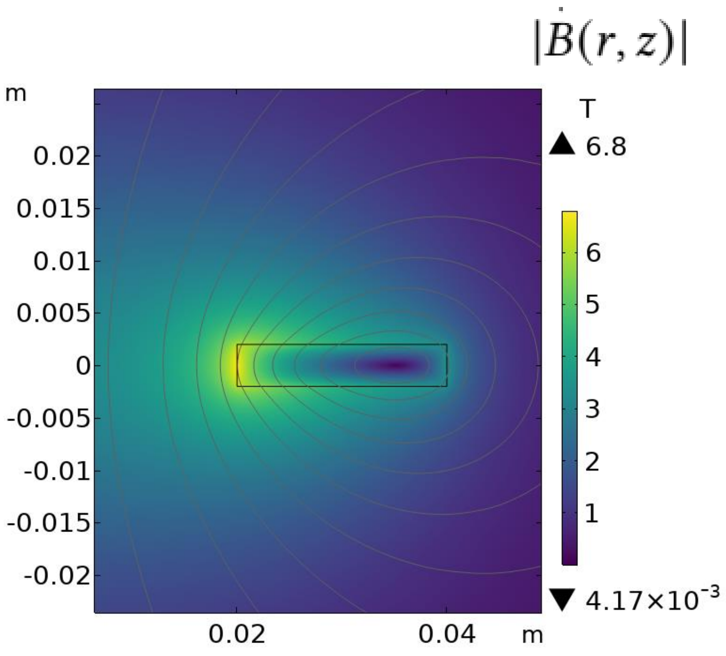


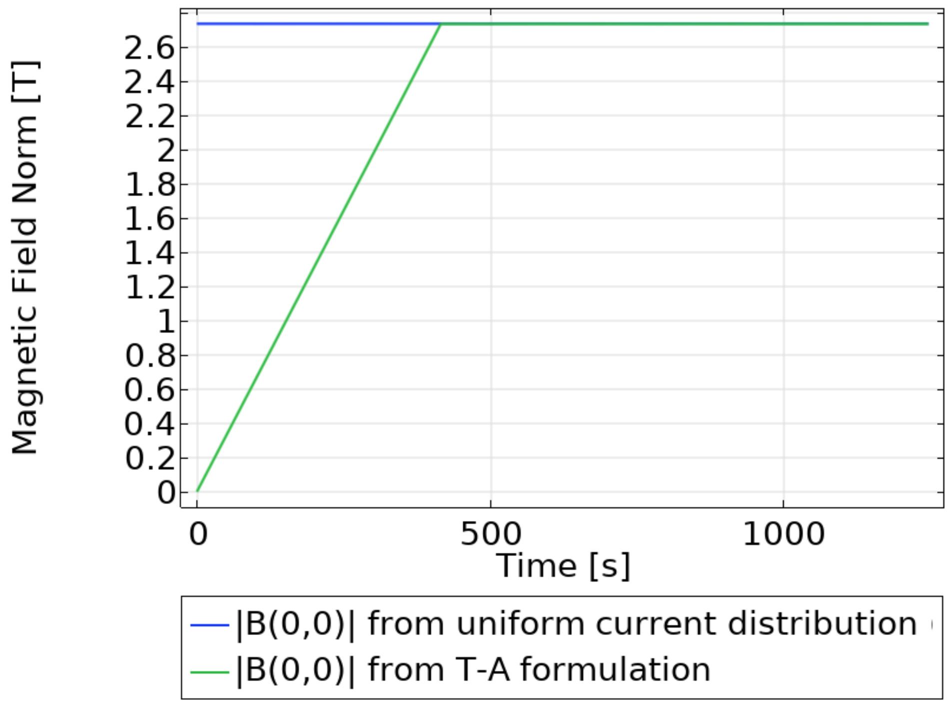
Magnetic field distribution in/around a single pancake coil

T-A formulation

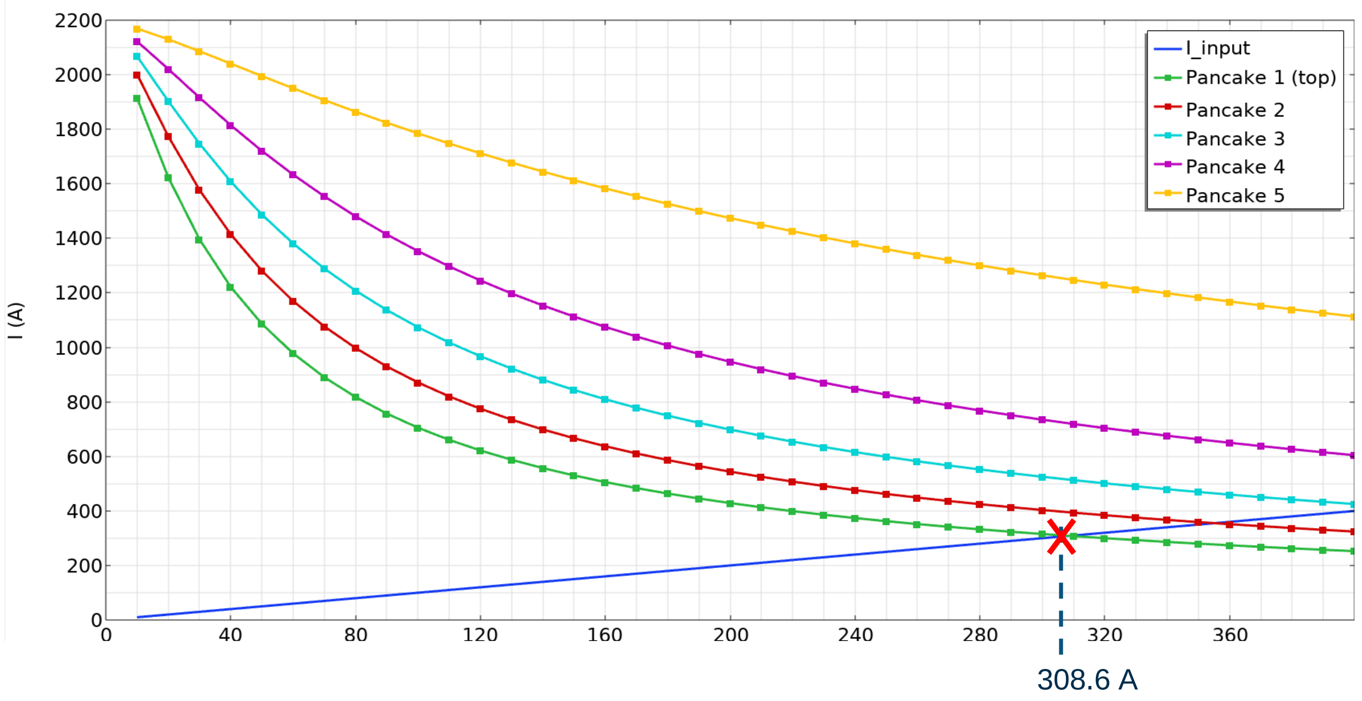


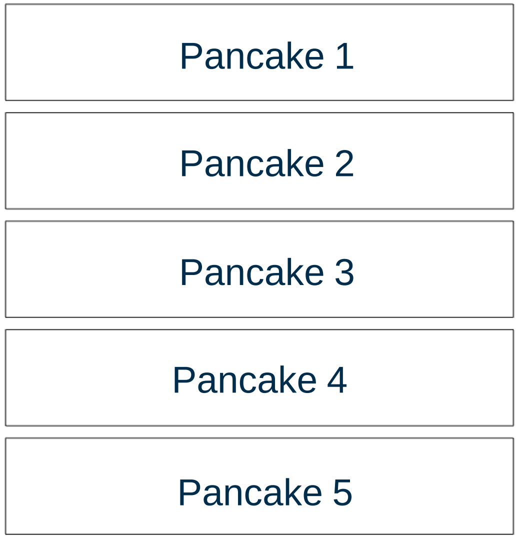
Uniform current distr.





Maximum input current for multiple pancake coils

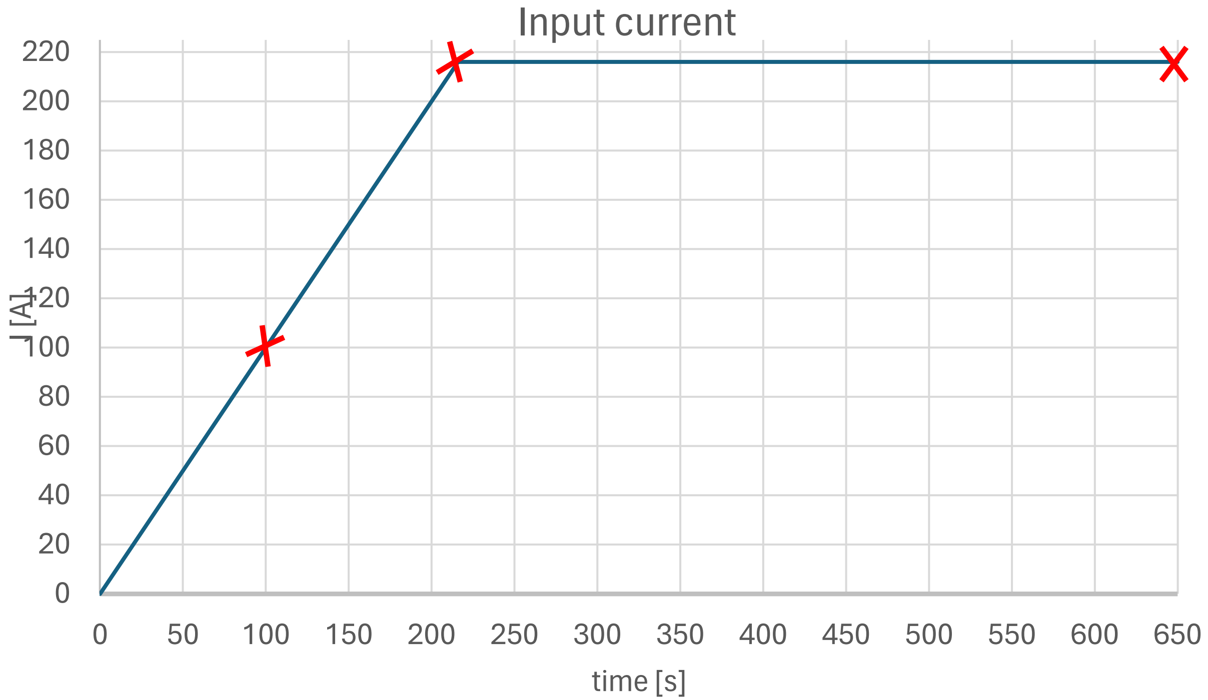


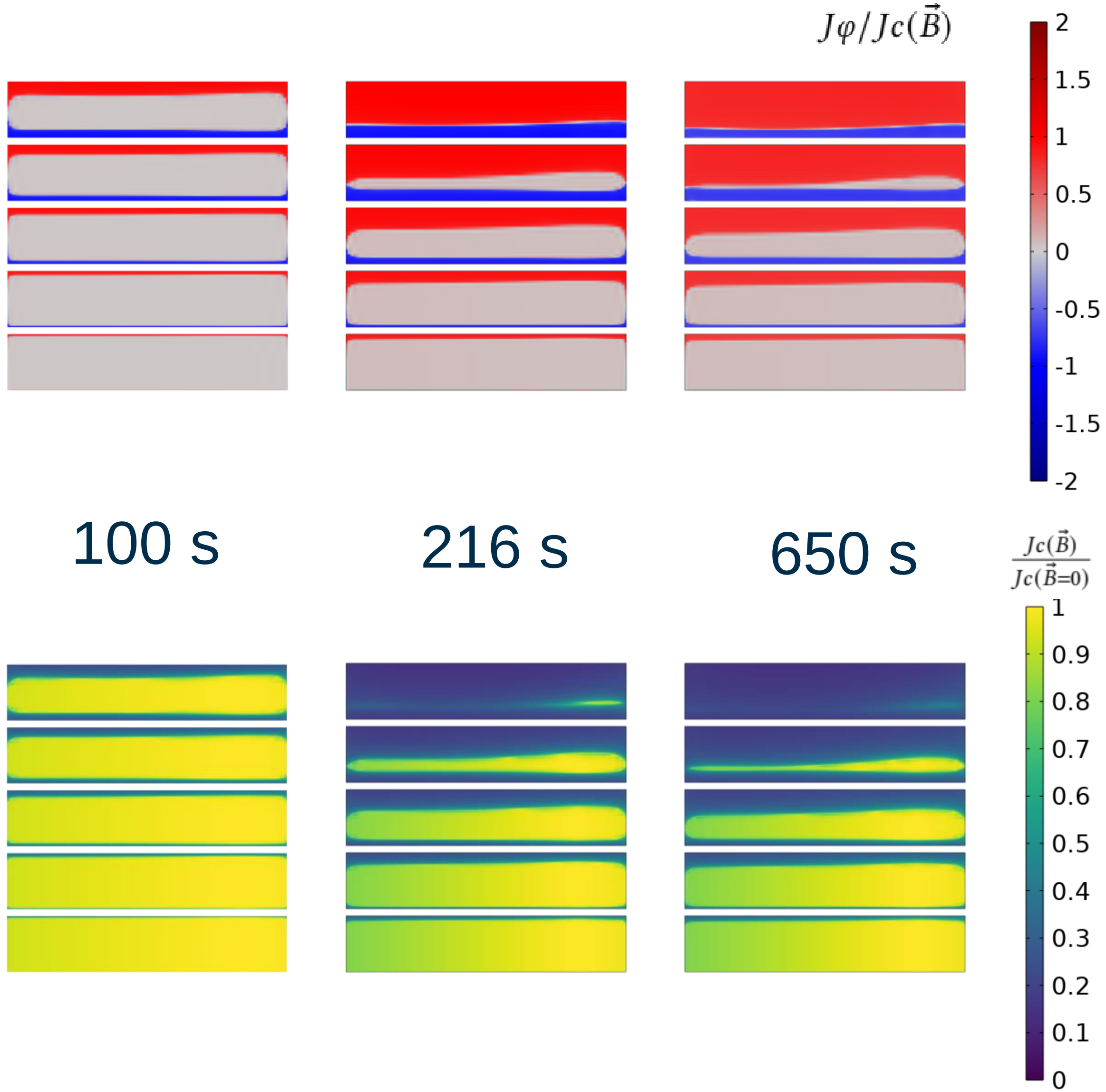


The minimum value at which the critical current curves intersect the applied current curve is 308.6 A

- ❑ From this method we find a maximum input current, Imax = 308.6 A
- ❑ The next analysis will consider a maximum input current of 0.7*Imax → Iop= 216 A

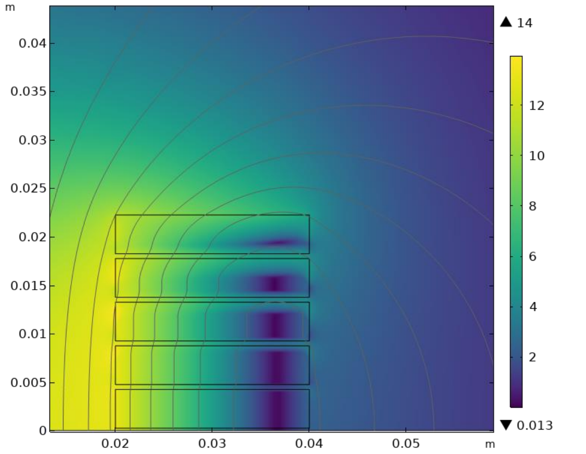
Magnetic field distribution in/around multiple pancake coils



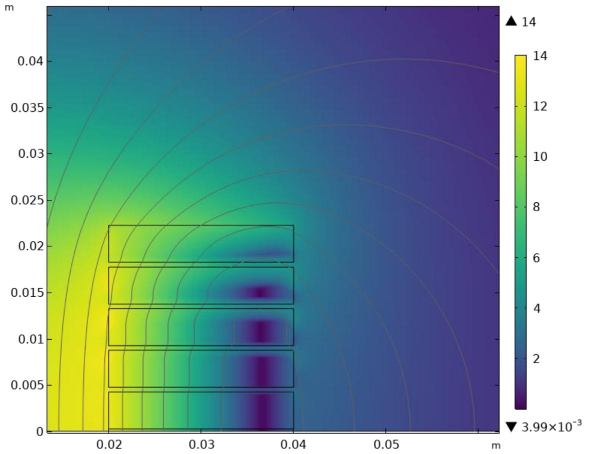


Magnetic field distribution: comparison between T-A formulation and uniform *J* distribution

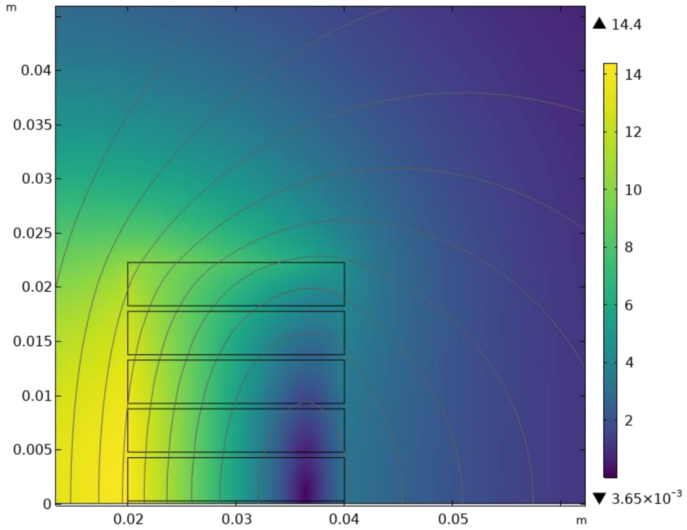
|B| after the ramp

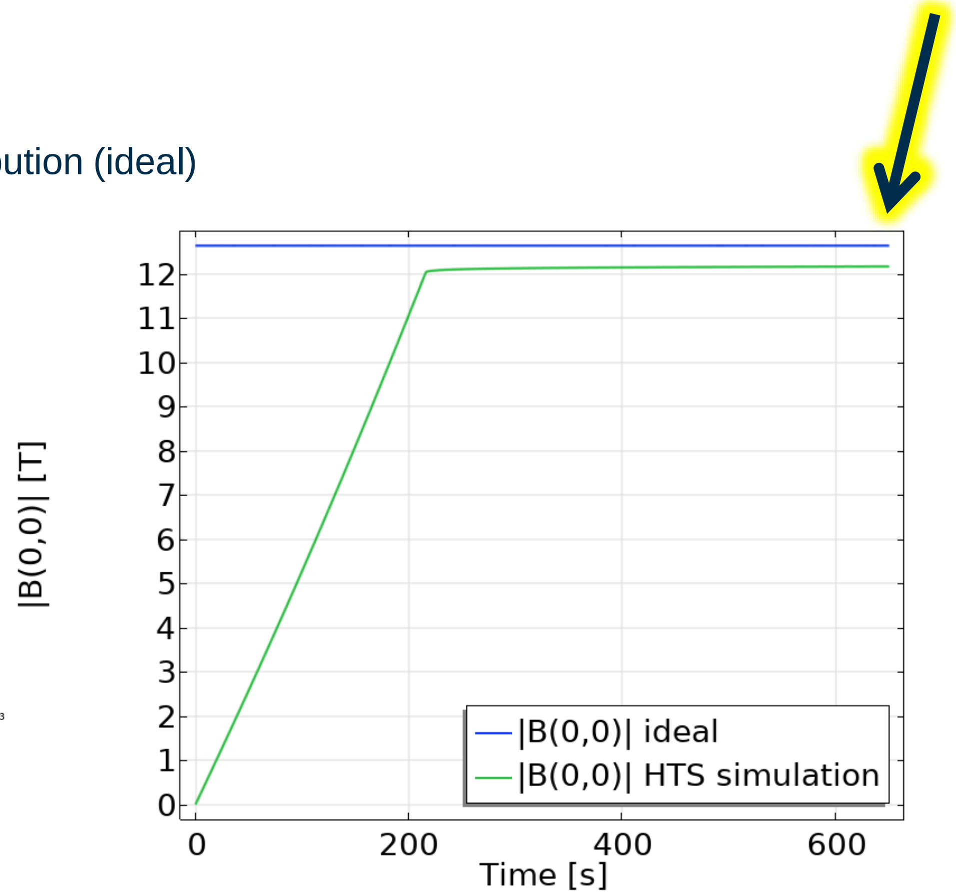


|B| at the end



|B| with uniform current density distribution (ideal)





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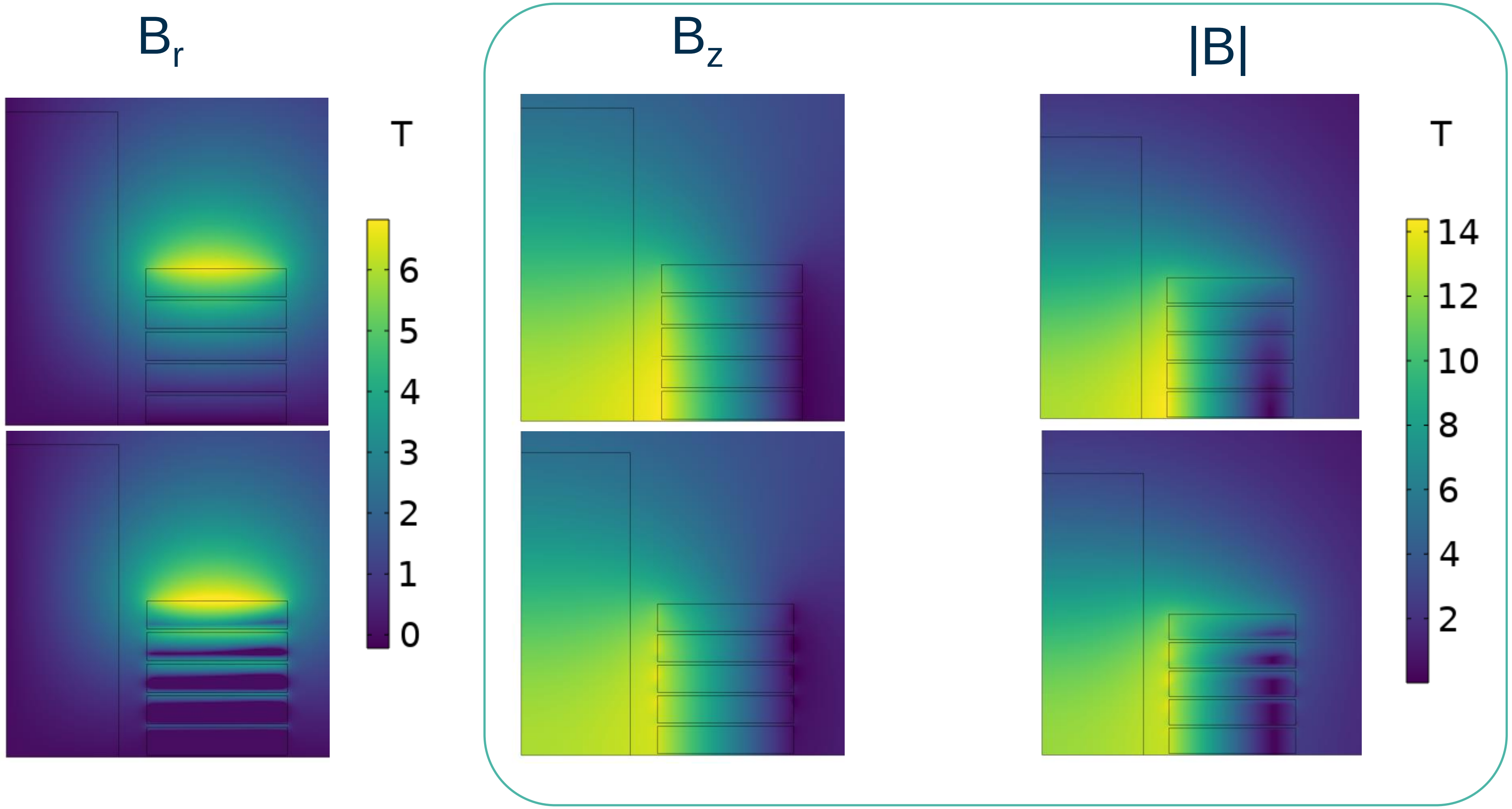
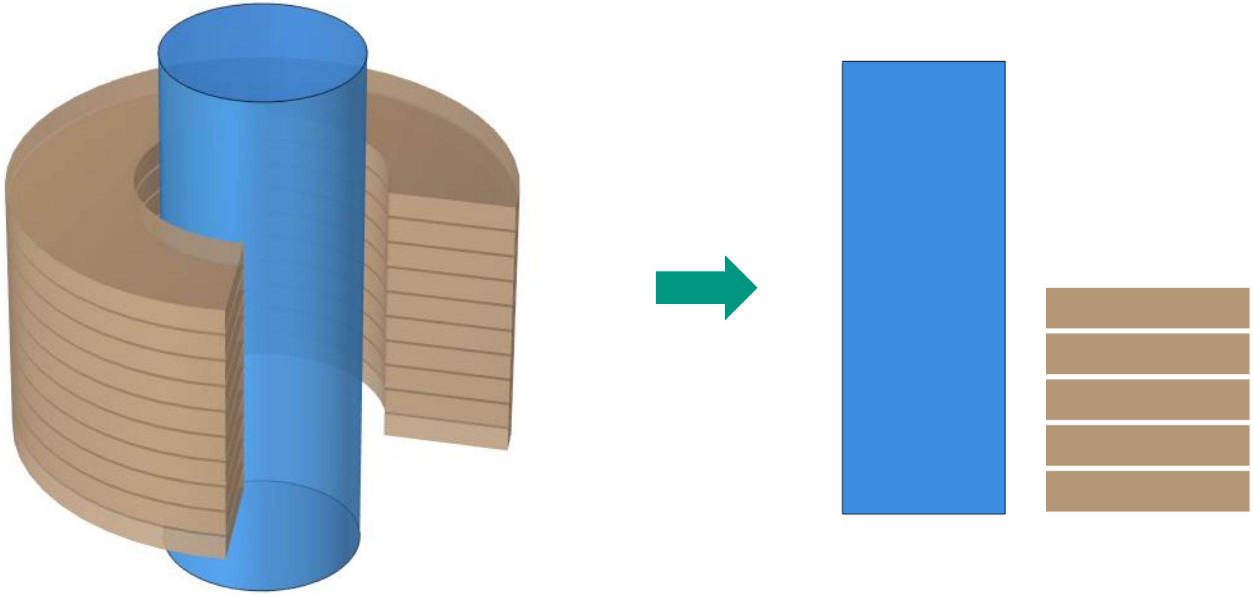
Magnetic field distribution: comparison between T-A formulation and uniform *J* distribution

Uniform current distr.

T-A formulation



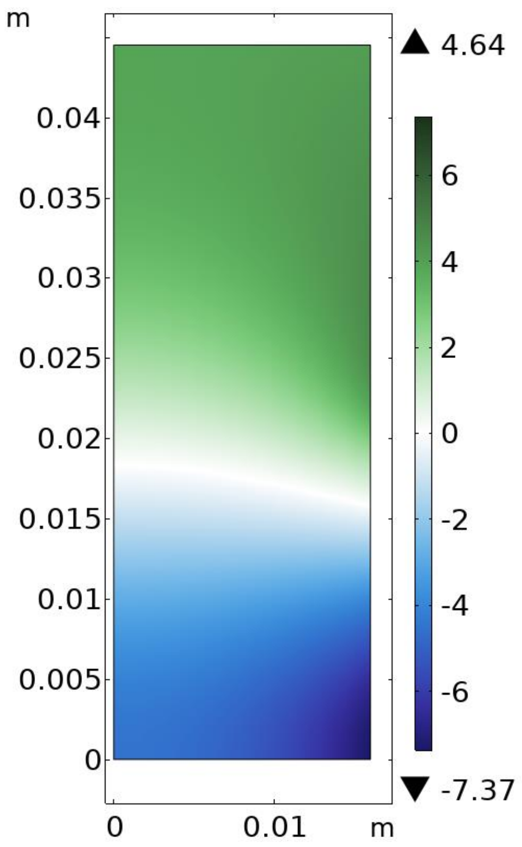
Quantification of the difference with respect to results obtained with uniform *J* distribution



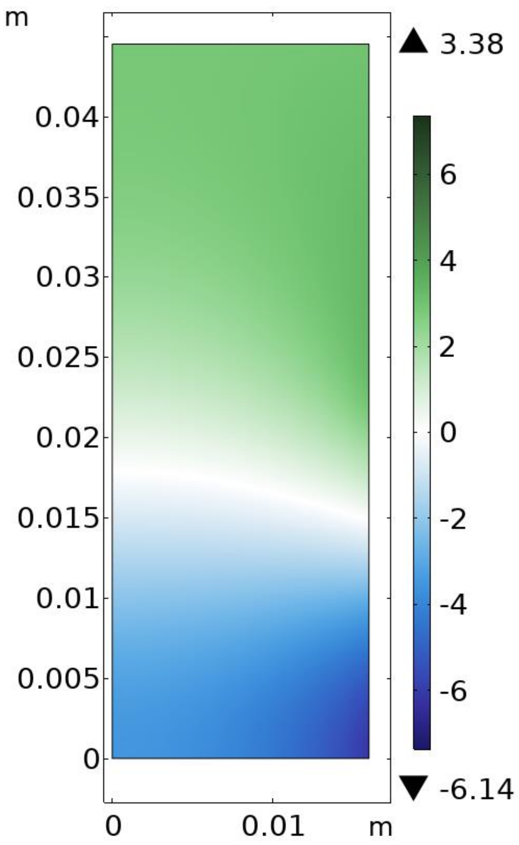
Magnetic field evaluated in a cylindrical volume extending outside the coil

Quantification of the difference with respect to results obtained with uniform *J* distribution

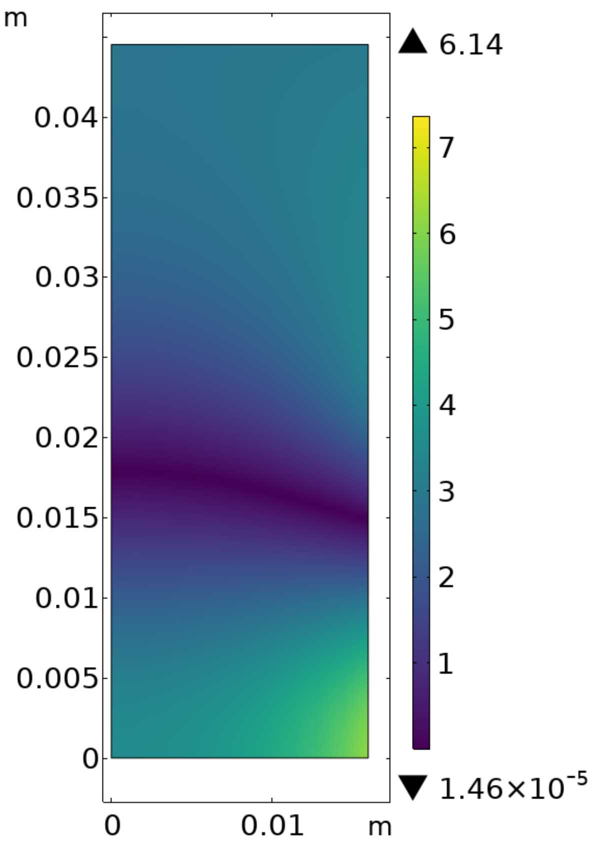
Δ|B|/Bid [%] after the ramp



Δ|B|/Bid [%] at the end



|Δ|B||/Bid [%] at the end



Slight decrease of the error after relaxation

Absolute value of error

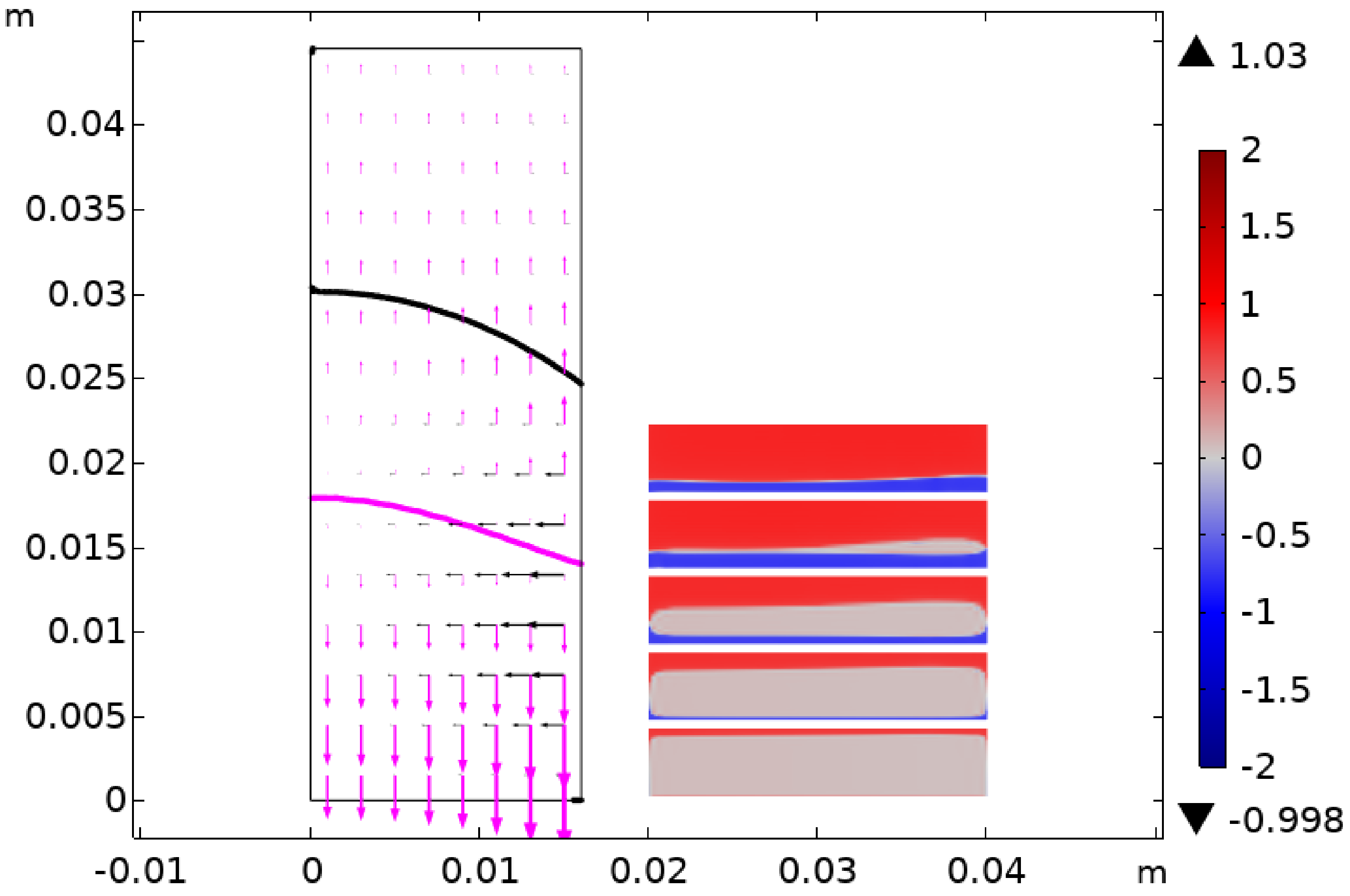
Quantification of the difference with respect to results obtained with uniform *J* distribution

R-direction arrows: Br_HTS-Br_unif

Z-direction arrows: Bz_HTS-Bz_unif

Black isoline: Br_HTS-Br_unif=0

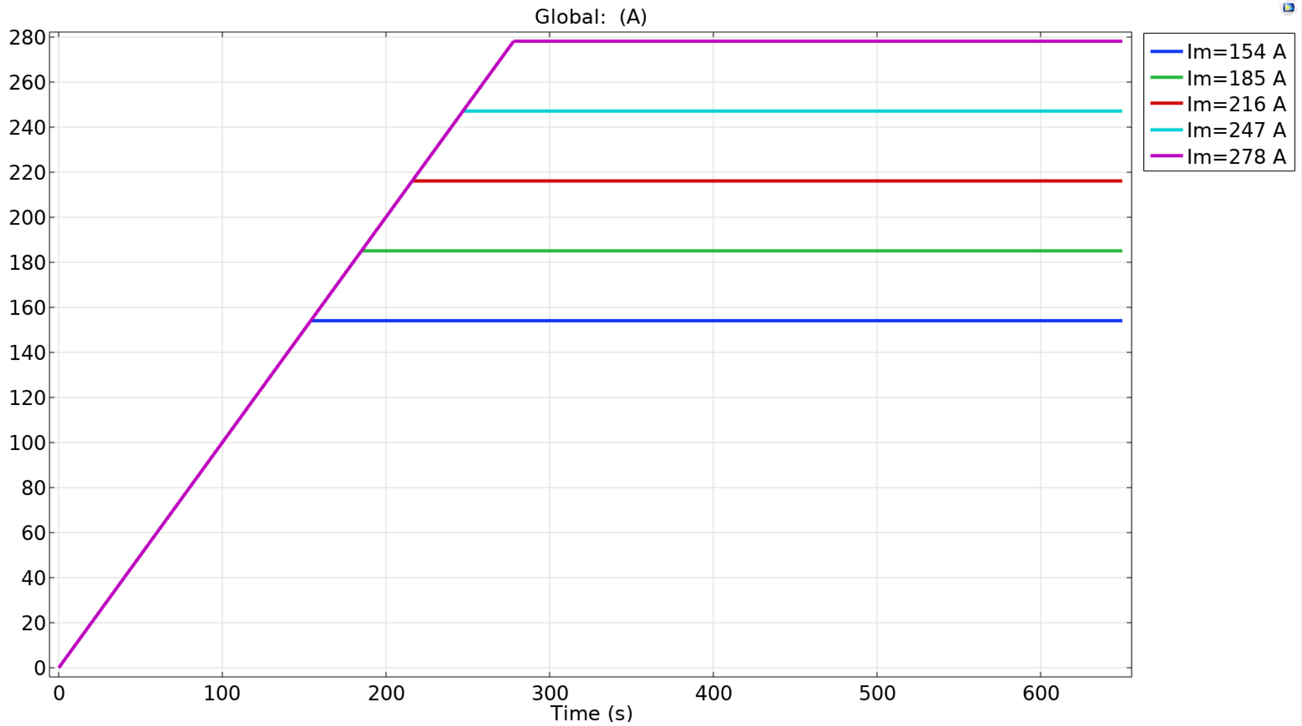
Magenta isoline: Bz_HTS-Bz_unif=0



Field Quality optimization
Increasing the input current

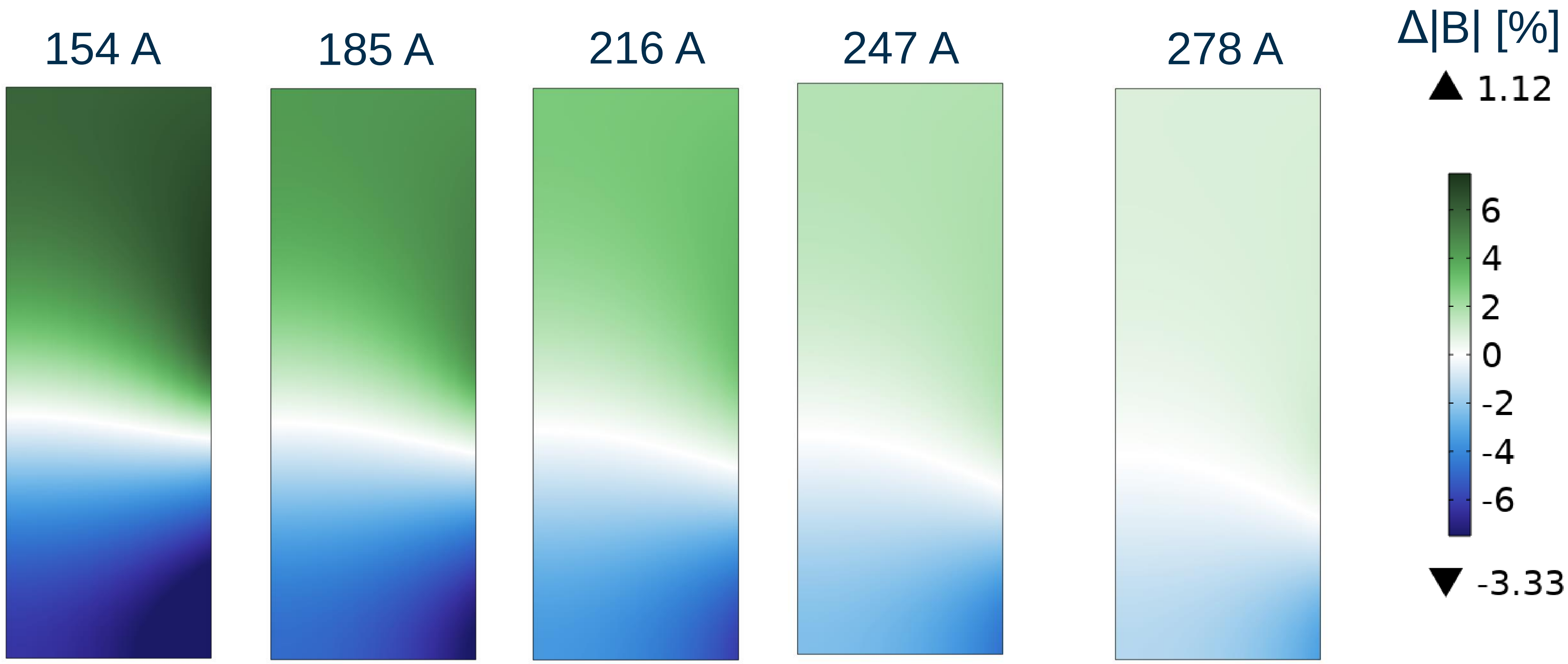
Effect of input current on field quality (with respect to field obtained with corresponding uniform current distribution)

1. 0.5 x I_c = 154A
2. 0.6 x I_c = 185 A
3. 0.7 x I_c = 216 A
4. 0.8 x I_c = 247 A
5. 0.9 x I_c = 278 A



All simulations run with a ramp of 1 A/s

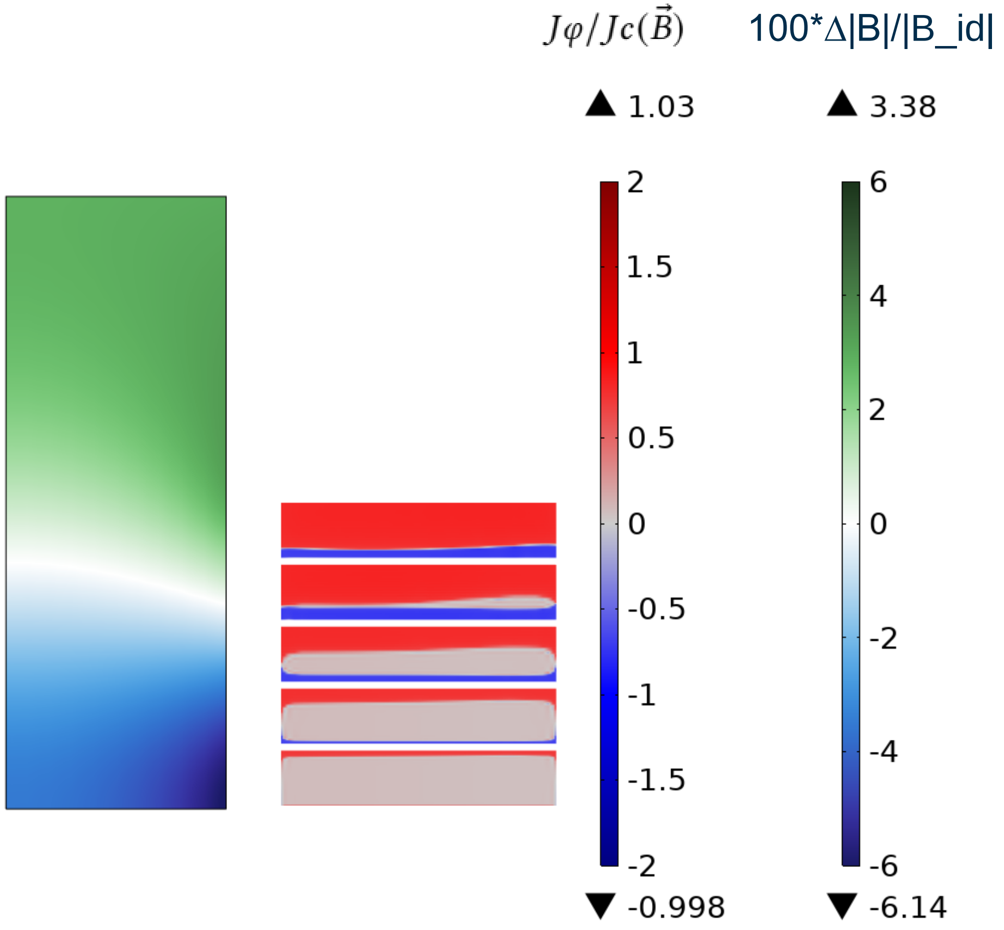
Effect of increasing input current
From Im=154 A to Im=278 A

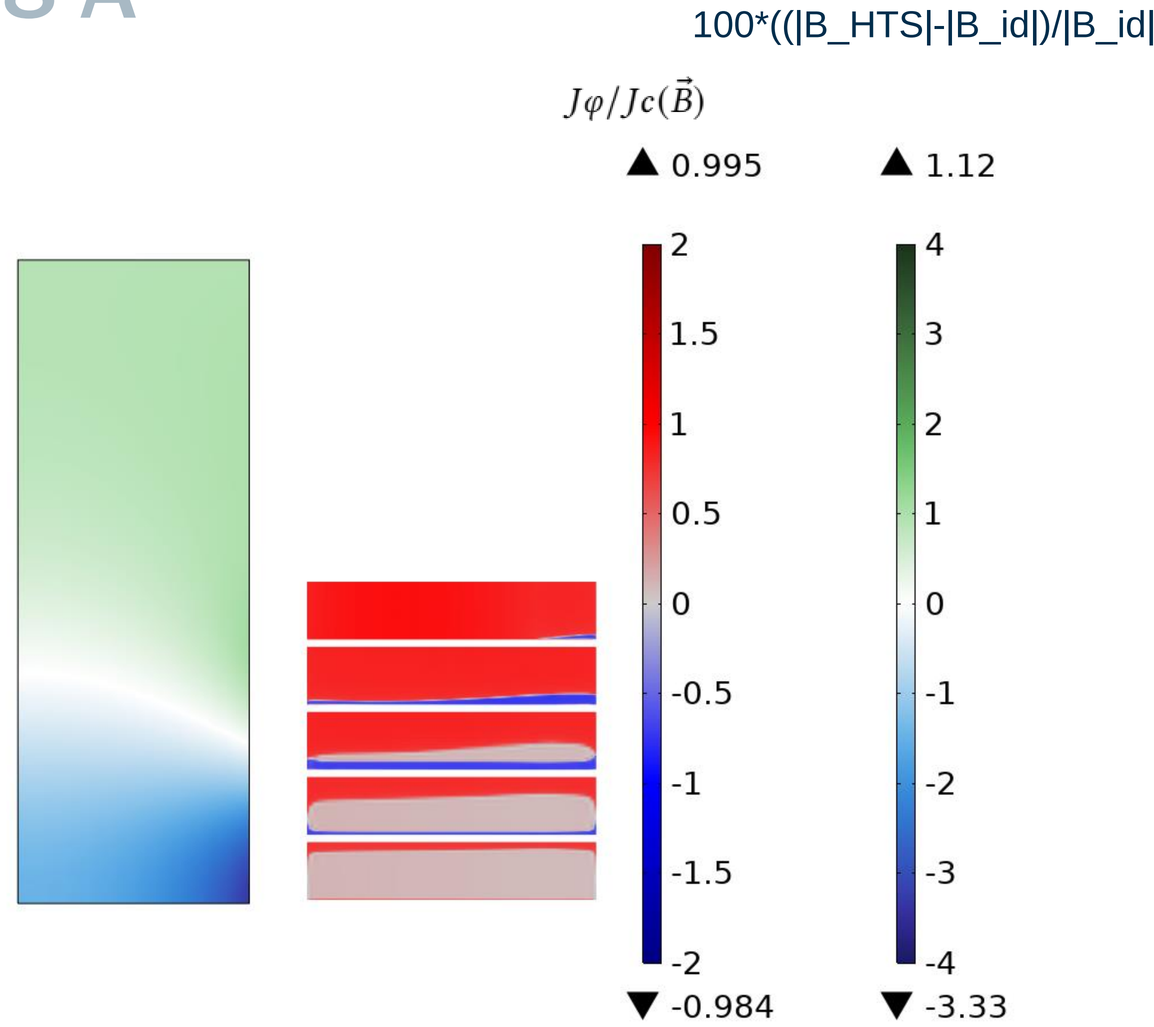


Error evaluated against corresponding result with uniform current distr.

Effect of increasing input current

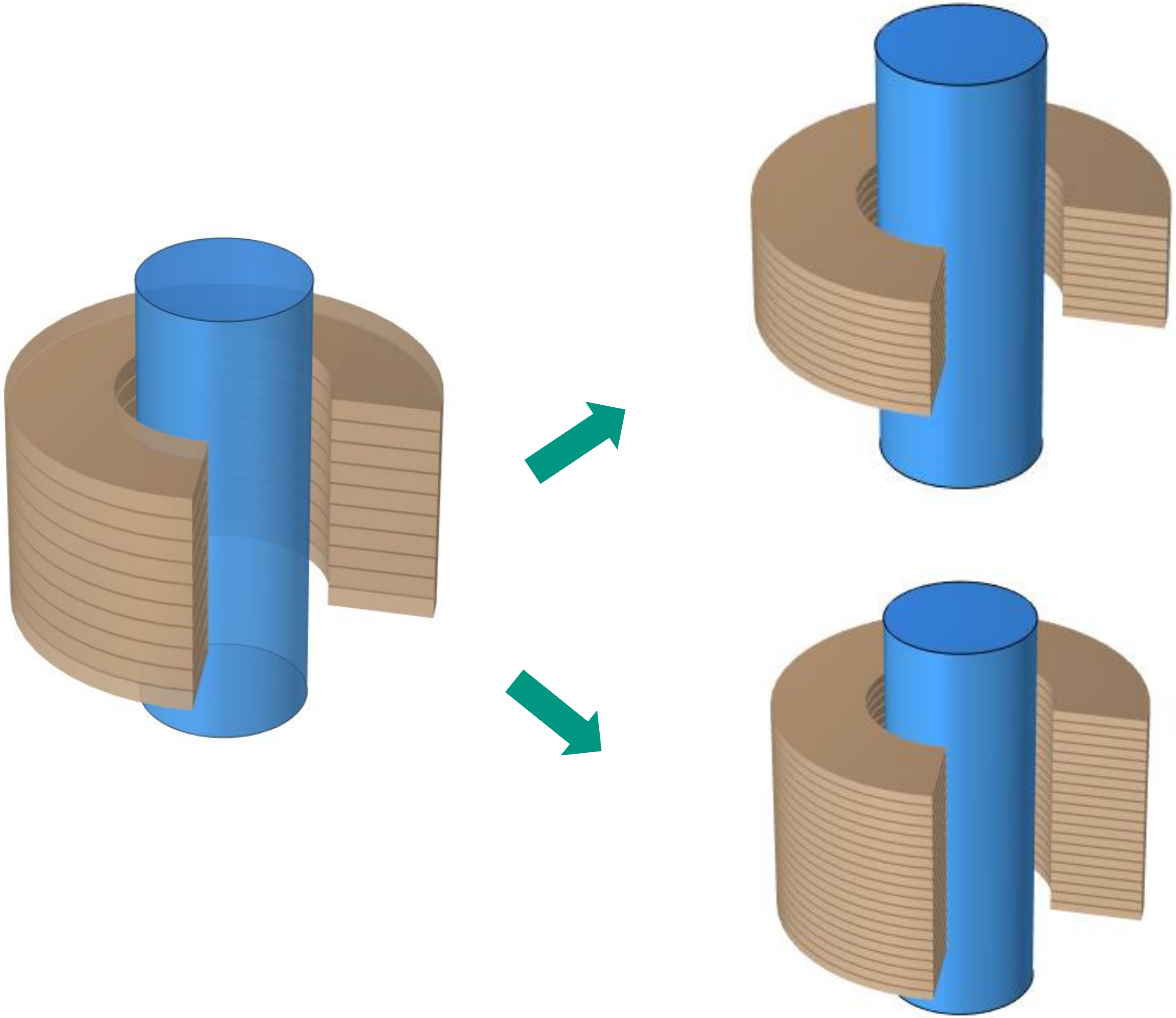
Comparison: Im=216 A vs Im=278 A





Error evaluated against corresponding result with uniform current distr.

Effect of using narrower tapes



Case 1

10 Pancakes half tape width

Same input current

Double J_c (realistic?)

Case 2

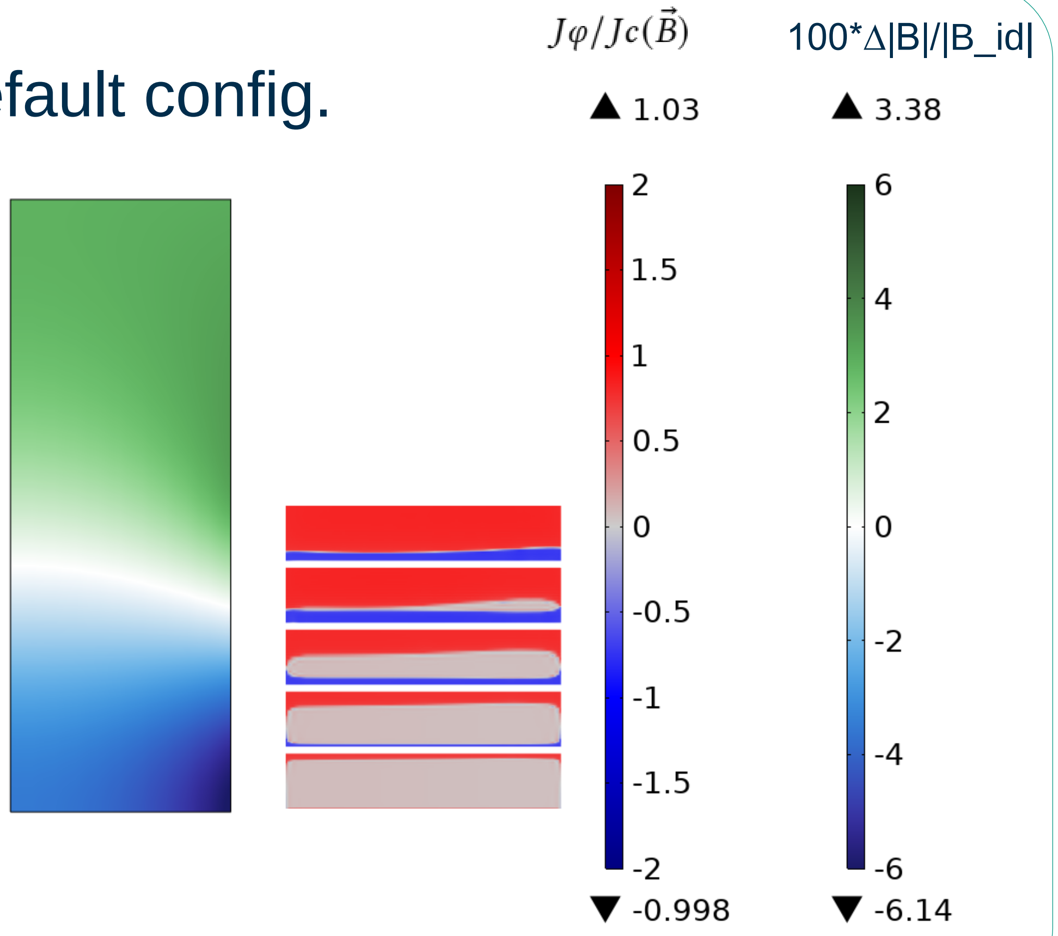
20 Pancakes half tape width

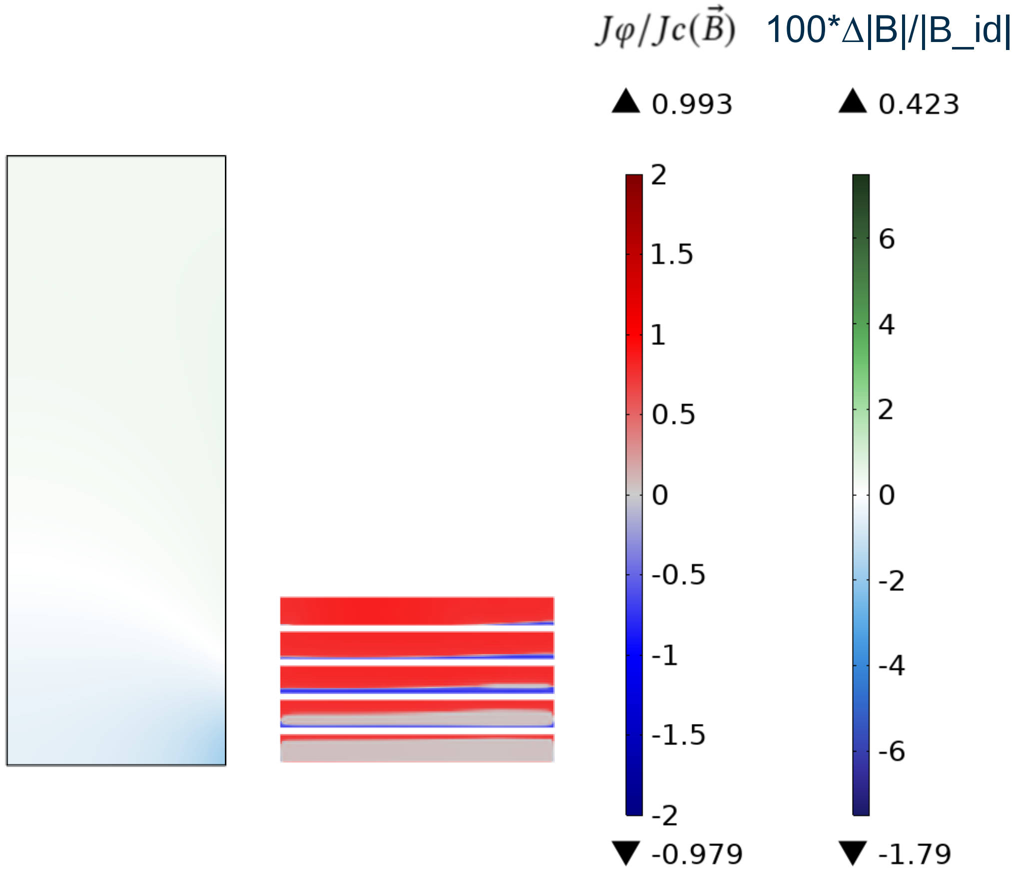
Half input current

Same J_c

Effect of using narrower tapes: case 1

Default config.

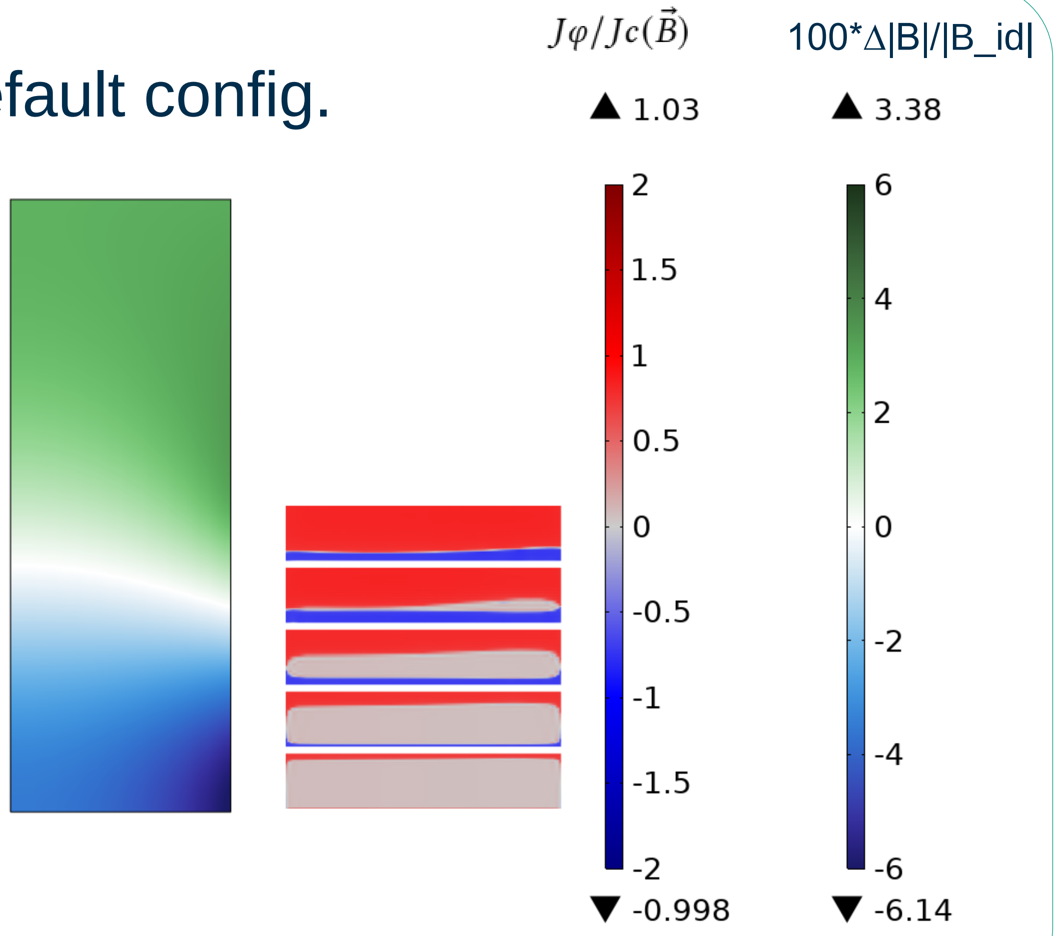


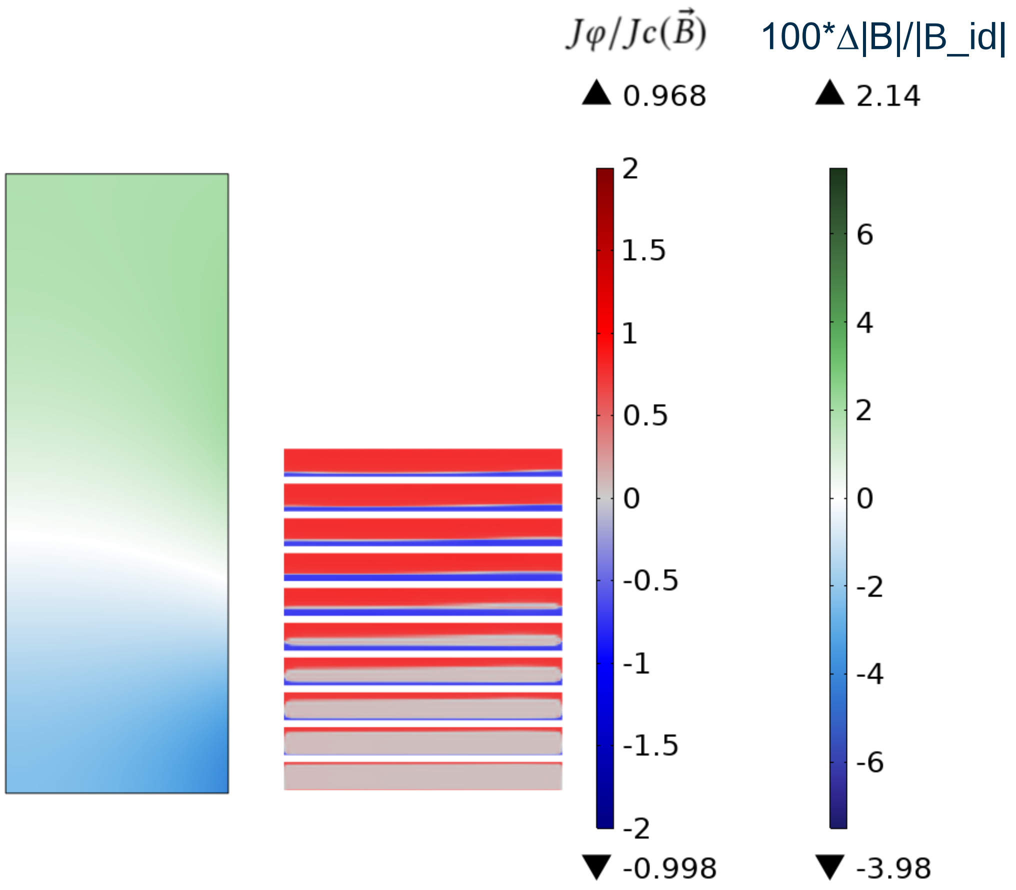


Error evaluated against corresponding result with uniform current distr.

Effect of using narrower tapes: case 2

Default config.

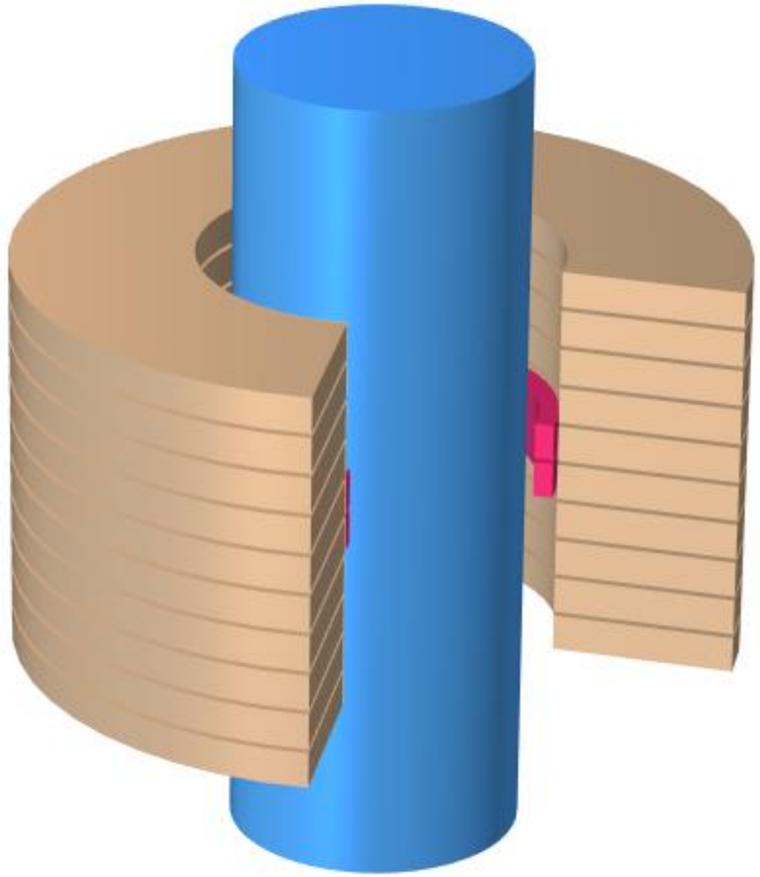




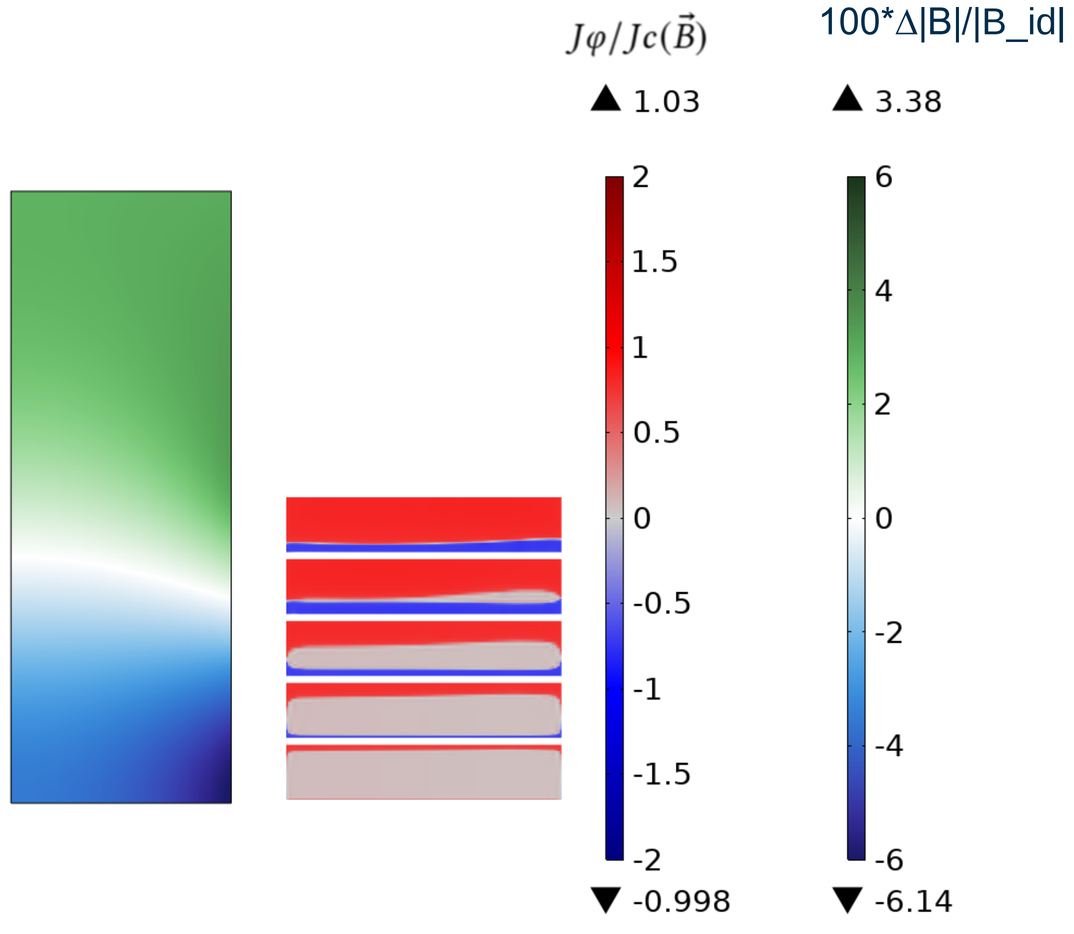
Error evaluated against corresponding result with uniform current distr.

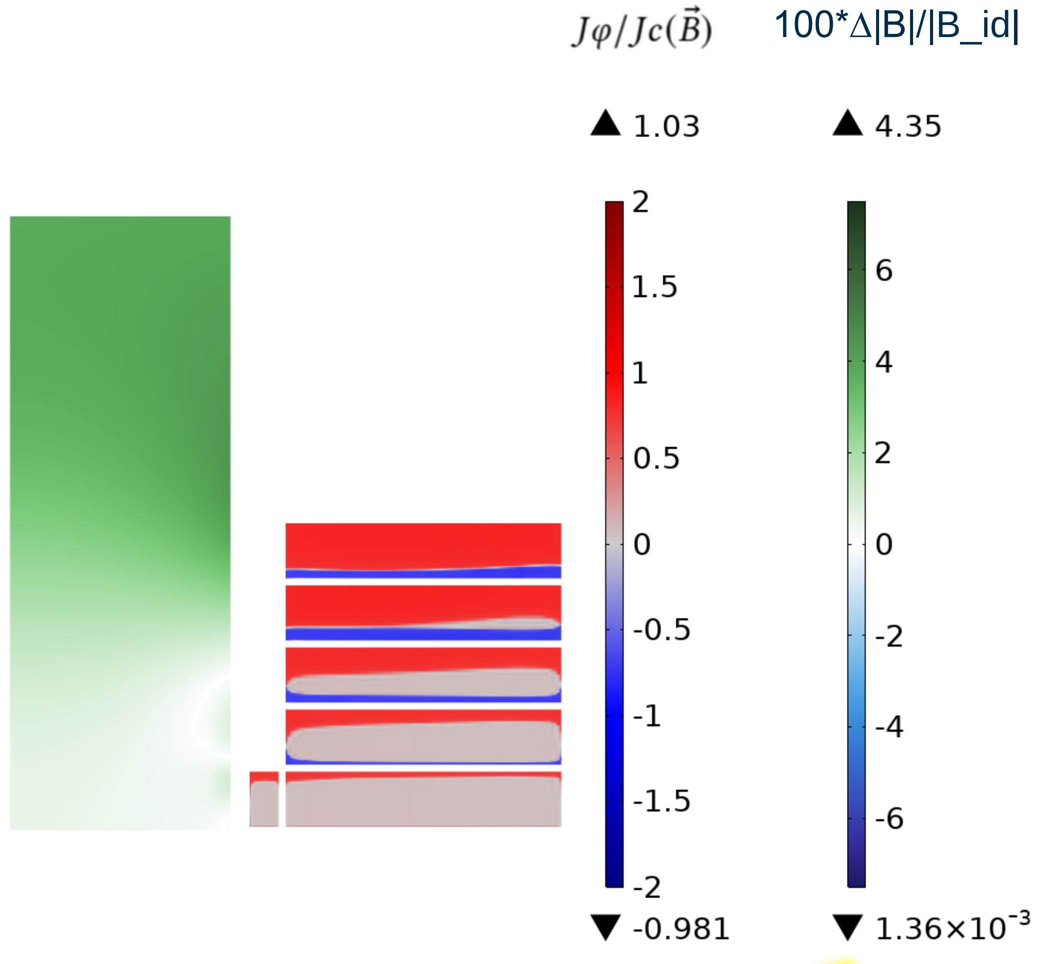
Can we reduce the error with additional coils?

- Double pancake coil to compensate the field distortion caused by screening currents
- Field correction of 0.5 T in (0,0)
- Series connection → 37 turns in each additional pancake coil



Effect of additional pancake coils

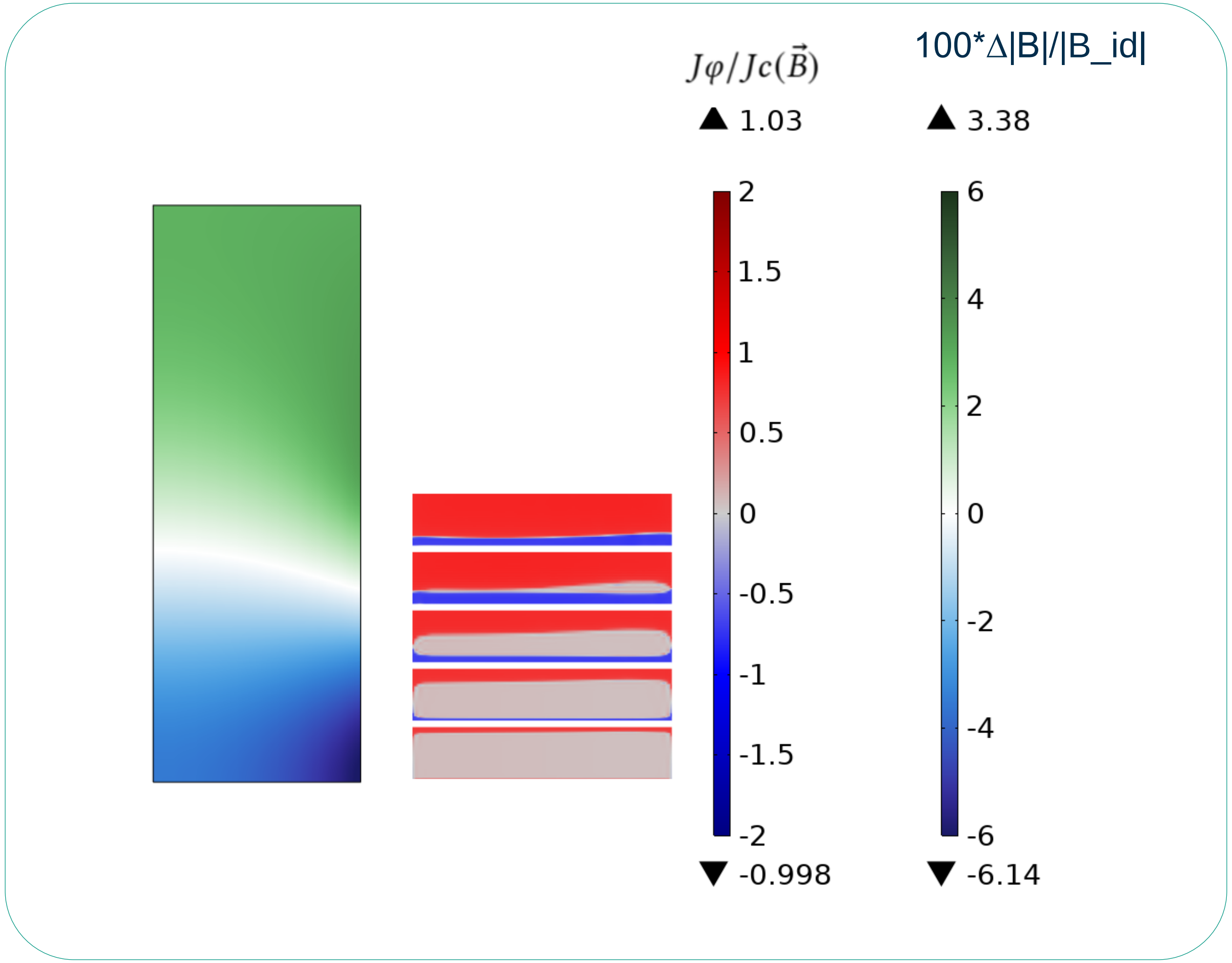


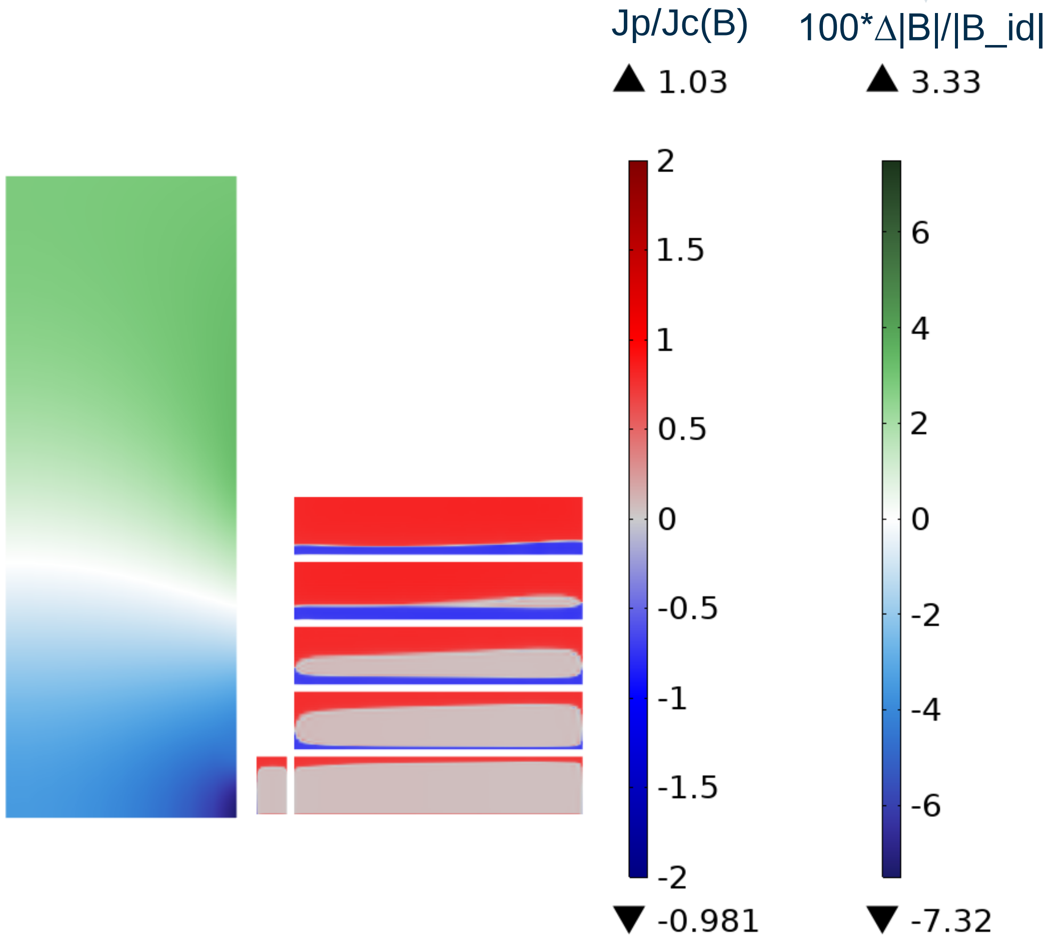


Error evaluated against result with uniform current distr. for default configuration (without extra pancake)

Effect of additional pancake coils

- B_id including double pancake

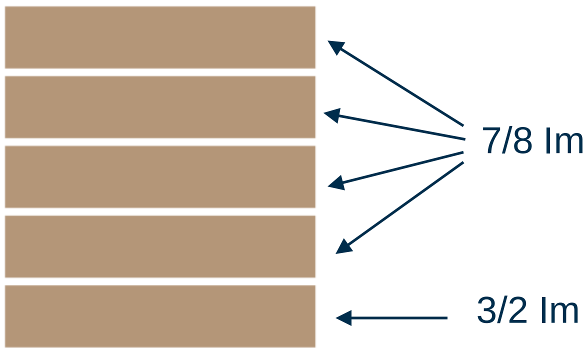


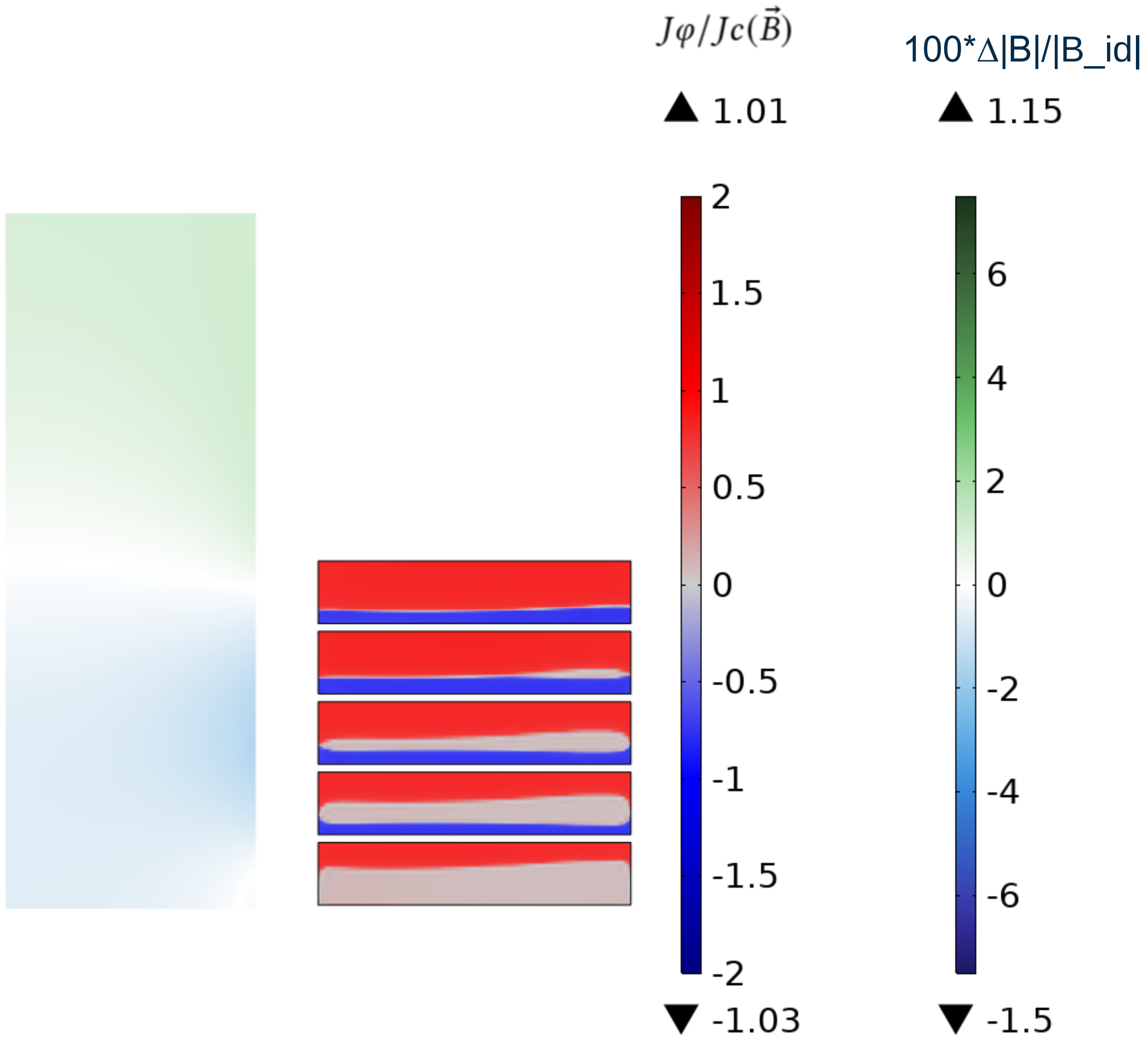


When compared against result with uniform current distr. for the analyzed configuration (with extra pancake), error increases

Alternative: increasing the current of the internal pancakes

- Current in central pancake increased by 50 %
- Current in other pancakes reduced accordingly

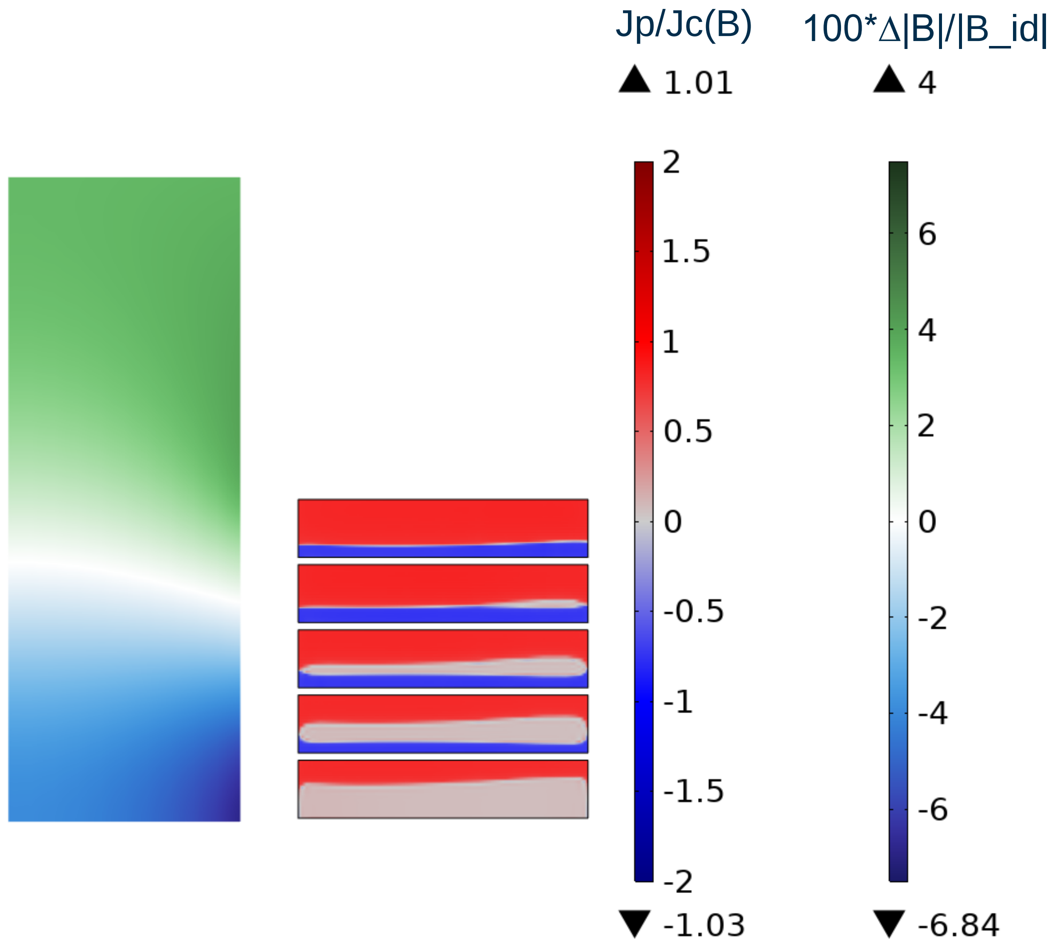




Error evaluated against result with uniform current distr. for <u>default configuration</u> (same current in each pancake)

Alternative: increasing the current of the internal pancakes

- B_id with same input current



Again, when compared against result with uniform current distr. for the analyzed configuration (more current in central pancakes), error increases

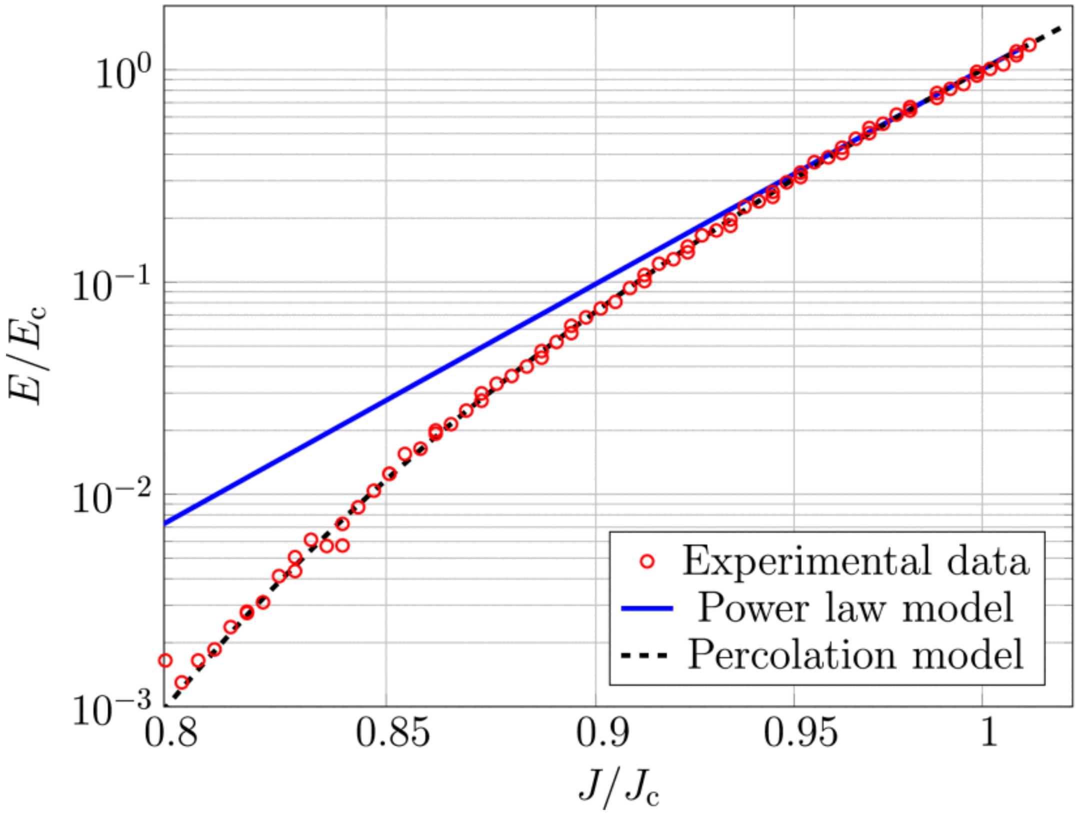
Summary

- Homogenized T-A formulation: efficient tool to evaluate influence of screening currents on magnetic field
- Field distributions compared with those obtained with model based on uniform current distribution for different magnet configurations
- Same approach can be used to study field uniformity in a region of interest

Contents

1. Introduction to T-A formulation
2. Effect of screening currents on magnetic field
3. What constitutive law for superconductors?

Beyond the *E-J* power-law



Source: Sirois *et al.* 2023 *IEEE Trans. Appl. Supercond.* **33** 9700101

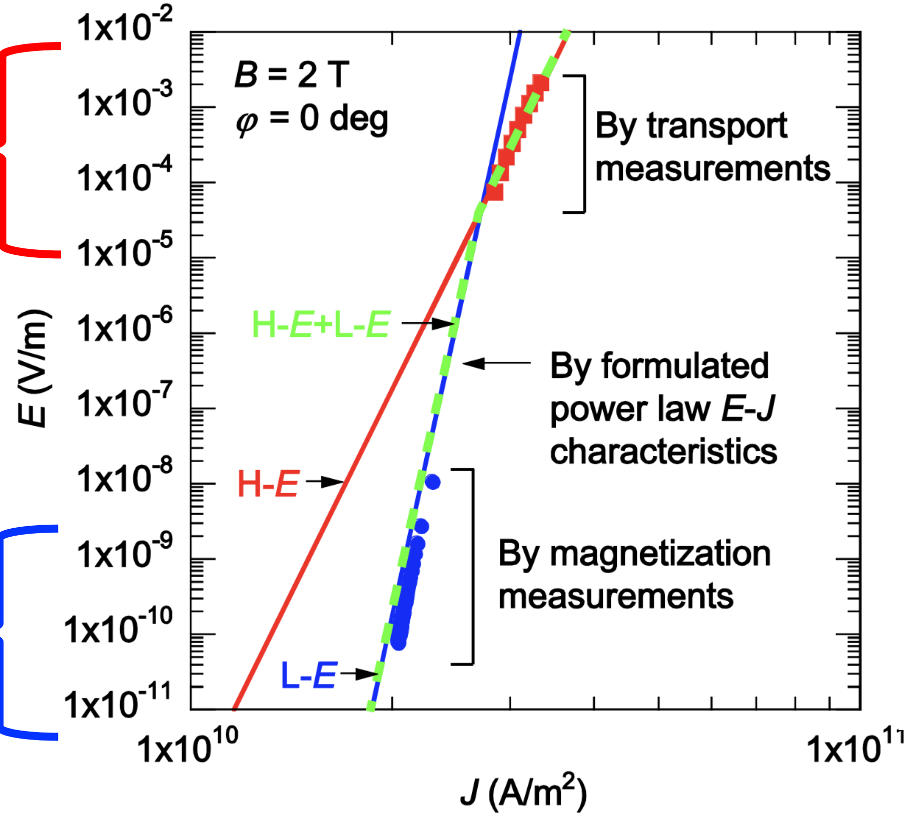
Beyond the *E-J* power-law

Power law near E_c

$$E = E_c \left(\frac{J}{J_c}\right)^n$$

Different behavior at low electric fields

Important for slow ramps, e.g. magnets



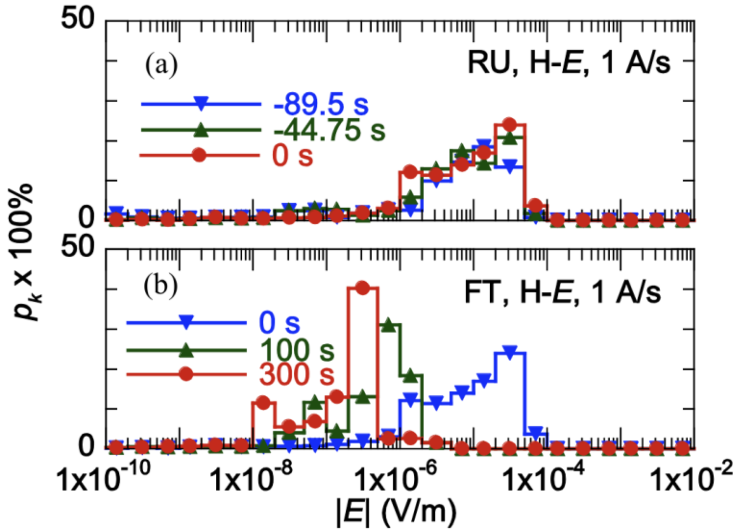
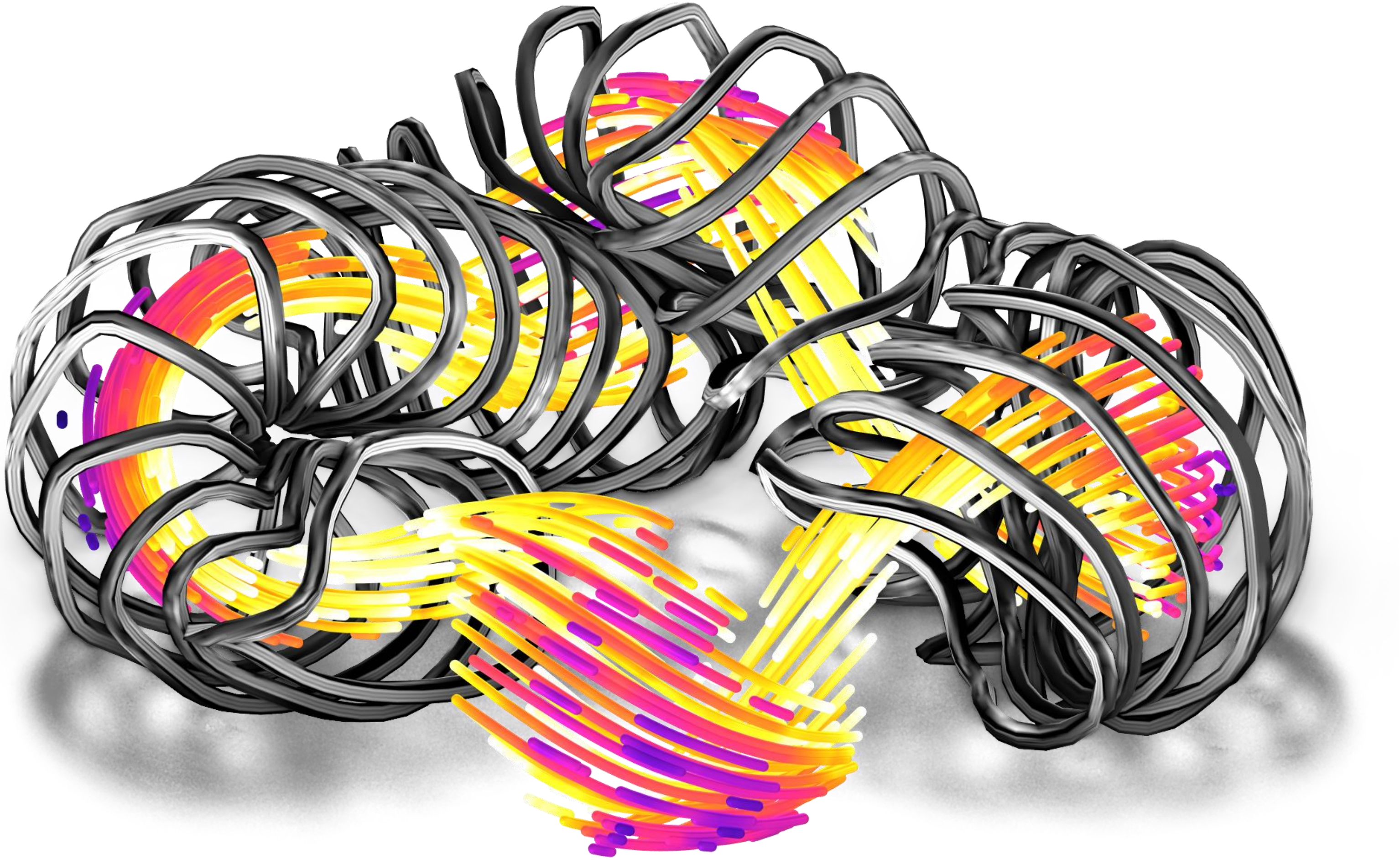


Fig. 5. Temporal evolution of the weighted probability p_k when *E-J* characteristic is H-*E* and ramp-up rate is 1 A/s at (a) the ramp up phase and (b) flat top. The ramp up phase begins at −179 s.

Source: Li *et al.* 2018 *IEEE Trans. Appl. Supercond.* **28** 4601105

Next steps

1. Apply this tool to cases of interest
2. Compare with case of NI coils (different model)
3. Extend these tools to 3D (non-planar coils)



Source: N. Riva and N. Strasser, Proxima Fusion